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ADVANCED COMPOSITE COST ESTIMATING MANUAL

NORTHROP CORPORATION
AIRCRAFT DIVISION
HAWTHORNE, CALIFORNIA 90250

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This technical report has been reviewed and is approved.

Richard J. Hirt

RICHARD J. HIRT
Project Engineer
Vehicle Synthesis Branch
Aeromechanics Division
AF Flight Dynamics Laboratory

FOR THE COMMANDER

Robert D. McKelvey

ROBERT D. McKELVEY, Col, USAF
Chief, Aeromechanics Division
AF Flight Dynamics Laboratory

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This program concentrated on the development of a computerized system that estimates the recurring costs associated with the fabrication of advanced composite detail parts and components. The system employs Industrial Engineering Standard equations developed in the program to calculate standard hours for the detail composite fabrication operations of layup, core preparation, part consolidation and finishing. With these standards as base, recurring costs are derived through the application of variance factors, improvement curve slopes and labor rates.

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PREFACE

This Technical Report was prepared by the Aircraft Division of Northrop Corporation under Contract No. F33615-75-C-3103 for the Air Force Flight Dynamics Laboratory, Air Force Wright Aeronautical Laboratories, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio. Mr. Richard J. Hirt, AFFDL was the Air Force Program Manager. This report covers the period from 1 April 1975 to 31 March 1976.

The work described in the report was carried out by Northrop Corporation, Aircraft Division, D. J. LeBlanc, Program Director. Principal contributors to the Northrop activities described in this report and their areas of responsibility are listed below:

Contributor	Responsibility
J. Lorenzana	Principal Cost Investigator
A. Kokawa	Cost Analysis
T. Bettner	Cost Analysis
F. Timson	Cost Analysis
J. Proctor	Cost Analysis
H. J. Behrens	Industrial Engineering
L. Lyle	Detail Engineering
M. Woo	Computer Programming
L. Bernhardt	Design and Analysis

D. J. LeBlanc, Program Director

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1.0 INTRODUCTION

1.1 BACKGROUND

The emerging cost consciousness within Government and Industry has resulted in a reassessment of the state-of-the-art cost estimating methodologies, particularly their applicability to new and developing technologies such as advanced composites. The basic problem that the Industry is confronted with in developing reliable estimating techniques for new technologies is the lack of a meaningful historical cost data base. Some sectors within the Government and Industry believe that this problem exists even in current established technologies such as conventional metals.

Cost has been a significant parameter in various advanced composites R & D programs funded by the Government. Improvements in design, manufacturing processes, equipment and material systems to reduce costs have been the goal of the majority of these programs. This emphasis on cost has accentuated the need for a reliable tool that can be used by Government and Industry for cost estimating, tradeoff analysis, allocation of research and production funds, and pricing.

1.2 OBJECTIVE

The objective of the "Advanced Composite Cost Estimating Manual Program," Contract No. F33615-75-C-3103 was to develop a computerized methodology for estimating the recurring costs associated with the fabrication for advanced composite parts, and to fully document this methodology for use by Government and Industry. This program was conducted by Northrop Corporation, Aircraft Division, from April 1975 to 31 March 1976.

This program represents the initial effort towards a long-range goal of achieving a capability for estimating, reliably and consistently, production costs of aircraft airframe structures. To provide a scope that was both meaningful and achievable within the program timeframe. The current program was limited to the fabrication of advanced composite detail parts. To achieve the long range objective, this methodology will be expanded to cover the fabrication of metallic parts as well as the subassembly and assembly of composite and metallic structures. The steps required in expanding this methodology are illustrated in Figure 1.

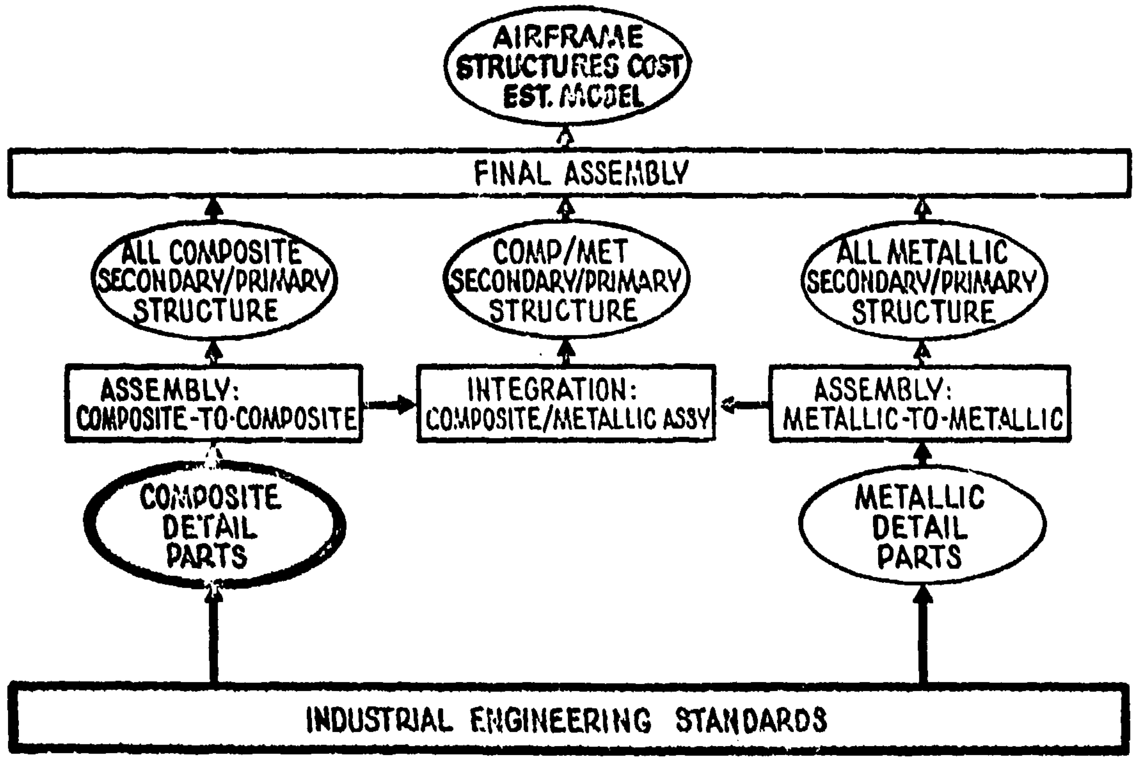


FIGURE 1. STEPS TO DEVELOP AN AIRFRAME STRUCTURES COST ESTIMATING MODEL

1.3 APPROACH

The ACCEM computerized estimating methodology utilizes Industrial Engineering Standards equations to calculate the pure labor standard hours associated with the detail fabrication operations performed in the manufacture of a composite part. These standard hours account only for the basic work content of a task and do not allow for other elements which are part of factory labor as experienced in a real production environment, such as fatigue, waiting time for tools and materials, attention to personal needs, etc. Figure 2 depicts the total work content of factory labor.

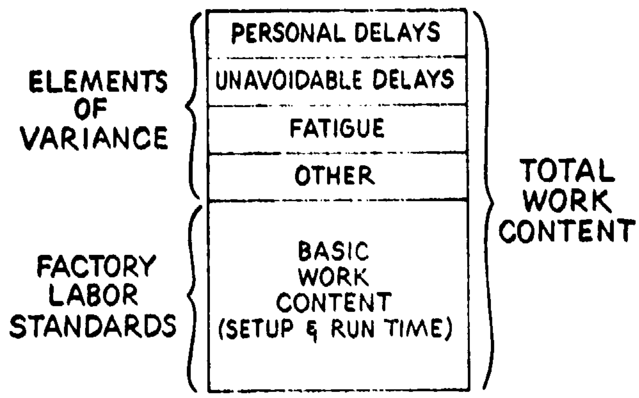


FIGURE 2. ELEMENTS OF FACTORY LABOR

Developing estimates of factory labor hours at specified units of production is accomplished by the application of appropriate variance factors and improvement curve slopes to the standards. These variance factors represents allowances for these elements which must be accounted for in estimating the total work content of factory labor. The procedure for applying these variances is illustrated in Figure 3.

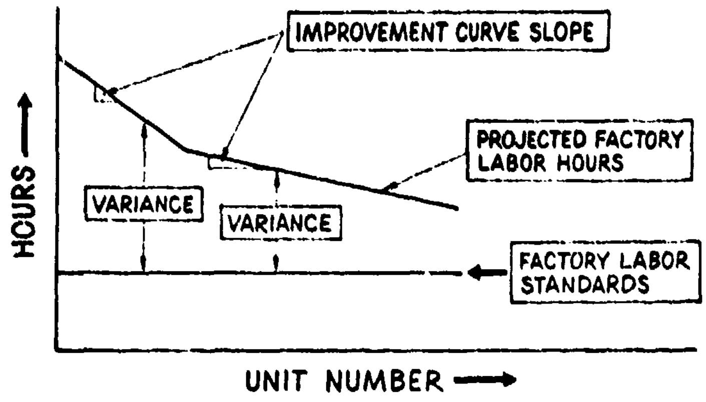


FIGURE 3. ESTIMATING FACTORY LABOR HOURS

Cost estimating relationships have been developed in this program to estimate the labor hours for the recurring support labor functions, i.e., engineering, quality control, tooling, manufacturing engineering, and graphic services. Total direct labor costs are calculated by the application of appropriate labor rates. Production material is estimated by applying unit raw material costs to the computer-calculated material usage. Support material and manufacturing allowances are estimated as functions of production material and factory labor costs. Overhead rates are applied to the direct labor and material costs to arrive at total recurring costs.

The Industrial Engineering Standards approach was selected over conventional parametric approaches for the following reasons:

- It estimates at the detail level and therefore identifies cost significant fabrication operations.
- It is sensitive to design and manufacturing processes making it a useful tool for tradeoff analysis.
- It provides a higher degree of accuracy in estimates because of the many part parameters that it relates to.
- It provides one consistent base for estimating.
- It can be expanded to cover conventional and advanced metals, assembly operations, new manufacturing methods and equipment, new design approaches and new materials.
- The computerization of all the Industrial Engineering Standard equations provides quick response time.

1.4 PROGRAM IMPLEMENTATION

The objective of this program was accomplished through the implementation of five (5) tasks:

Task 1	Data Research
Task 2	Development of Industrial Engineering Standard Equations
Task 3	Development of Support Functions Estimating Relationships
Task 4	Development of Cost Projection Factors
Task 5	Documentation

DATA RESEARCH: Throughout the program, pertinent data was solicited from various Government and Industry sources. "The Structural Fabrication Guide for Advanced Composites," a program conducted by Lockheed-Georgia Company and assisted by Grumman Aerospace Corporation, Aeronautical Research of Princeton (ARAP), and Pratt and Whitney Aircraft Division of United Aircraft Corporation provided an insight to the quality and quantity of data available within the Industry. It also provided guidelines in the identification, definition and catergorization of the composite fabrication processes.

Detail drawings and actual hours data provided by Boeing Corporation, Bell Helicopter, and McDonnell-Douglas, St. Louis, were used in assessing and evaluating the projection factors developed in this program. The Advanced Composite Design Guide prepared by the Los Angeles Aircraft Division of Rockwell International Corporation was used to promote a better understanding of the various advanced composite fabrication processes. Composites-related literature provided the team with an overview of various cost estimating techniques used within the Industry. It also provided guidelines on improvement curves and variance factor development. Northrop's fiberglass data was used extensively in this program. Support labor estimating relationships and cost projection factors were developed almost entirely from this experience.

INDUSTRIAL ENGINEERING STANDARDS EQUATIONS: Industrial Engineering Time Standards were developed through stopwatch observations of graphite and fiberglass fabrication at Northrop. The stopwatch time study technique involves the actual time measurement of a defined task performed by a qualified operator working at a normal performance level in accordance with a specified method. This technique was first applied to advanced composites in the "Advanced Development of Not-Critical-To-Flight-Safety Advanced Composite Aircraft Structures Program" (NCTFS) Contract No. F33615-72-C-1781, conducted by Northrop Corporation Aircraft Division. The detail procedures followed in establishing these time standards included:

- Defining the task and its elements
- Recording actual and lapsed times for each observation
- Rating the operator's performance level
- Adjusting recorded actual times based on operator's performance rating

- Establishing ranges for adjusted recorded times

- Tabulating the standard times by range

This technique was used in this program to establish standards for graphite woven material handling and layup, and for operations related to the trimming and drilling of cured composite parts.

The tabulated standards for composites were transformed to mathematical equations for computer applications. Representative graphs that correspond to these equations were also prepared to provide the user with a visual tool for manual application.

DEVELOPMENT OF SUPPORT LABOR ESTIMATING RELATIONSHIPS: Cost estimating relationships for support labor functions were derived from data generated by Northrop's fiberglass experience. These relationships define support labor as a function of factory labor hours. The equations that express these relationships are described in detail in this report. An option has been provided in the computerized methodology allowing the user to enter his own factors or relationships for support labor.

DEVELOPMENT OF VARIANCE EQUATIONS: Variance factors that are applied to the standards in calculating factory labor hour were developed from detailed analyses of Northrop's fiberglass data. Actual hours for each fabrication process category were plotted and curves fitted through these data points. Three types of curve functions were investigated. These are: arithmetic, logarithmic and hyperbolic. The "Dog-Leg" theory was also investigated. Results of this analysis are presented in detail in this report. The user has the option of either applying these factors, or of entering his own.

1.5 SCOPE

This computerized methodology was designed to estimate only the recurring costs associated with the fabrication of composite parts. Recurring costs are those incurred by all departmental elements for their repetitive and sustaining effort associated with and in support of the serial manufacture of a part. These costs are highly sensitive to design and manufacturing processes and provide a responsive criteria for evaluating the cost effectiveness of these parameters. Recurring costs include Factory Fabrication Labor, support labor functions for Engineering, Quality Control, Tooling, Manufacturing Engineering, and Graphic Services; Production and Support Material; indirect charges such as Labor and Material Overhead and General and Administrative costs. These elements are illustrated in Figure 4.

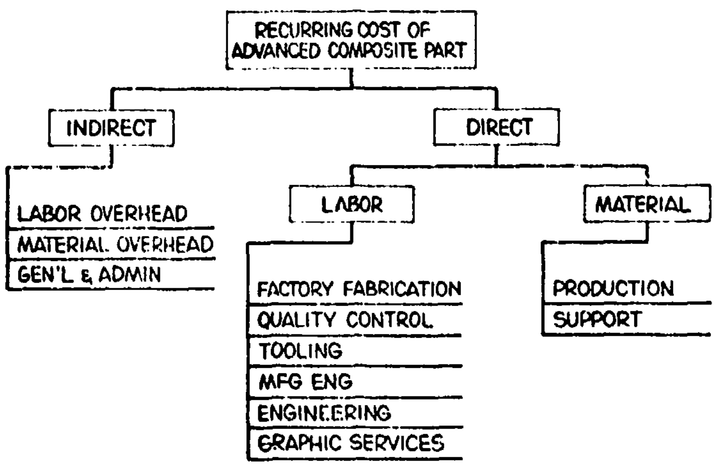


FIGURE 4. RECURRING COST OF ADVANCED COMPOSITE PART

Factory Fabrication Labor is the direct effort required to transform production raw material to the final advanced composite part. The factory fabrication processes covered in this methodology have been grouped into four major categories: Layup, Honeycomb Core Operation, Part Consolidation, and Finishing. The layup program includes, in addition to the basic deposition of

composite material, ply handling, cutting, debulking, and draping over contoured tools. Aluminum honeycomb core operations includes raw stock sawing, machining, core forming and stabilization. Part consolidation includes vacuum bagging; autoclave, oven, and elastomeric curing; bonding of detail parts; and splicing of core elements. Finishing encompasses all trimming and drilling operations performed on a cured part.

The mechanical assembly or consolidation of detail parts was not considered in this program.

The estimating methodology was developed from observations of graphite and fiberglass operations. Provisions have been made to incorporate other composite materials when data becomes available.

1.6 ORGANIZATION

This report is composed of three volumes:

Volume I	Advanced Composite Cost Estimating System Development
Volume II	User's Manual
Volume III	Backup Data

Volume I describes the elements of the cost estimating system. It discusses the development of Standards Estimating Relationships (SER's), Cost Estimating Relationships (CER's), and Cost Projection Factors.

Volume II describes the implementation of the computerized estimating system. Instructions for completion of the input forms, program listings, and a description of the outputs are also presented in this volume to further aid the user in understanding the procedures to be followed in using this system.

Volume III is an indexed compilation of all backup data used in developing this system.

ESTIMATING METHODOLOGY: The computerized methodology is composed of three routines:

1 - Factory Labor Standards Estimating
2 - Support Function Estimating
3 - Cost Projections

These routines are described in detail in this report.

OUTPUTS: The computerized cost estimating system generates a printing of the input data in coded form and of the calculated costs of advanced composite part fabrication. These outputs may be outlined as follows:

- GENERAL
  - IDENTIFICATION OF ESTIMATOR AND PART THAT IS ESTIMATED
  - QUANTITY OF EACH INPUT FORM
- LAYUP
  - CODED FORM OF INPUT DATA
  - STANDARD SETUP AND RUNTIME HOURS FOR DETAIL LABOR ELEMENTS
  - MATERIAL USAGE AND SCRAP
  - WEIGHT AND COST OF COMPOSITE MATERIAL
- HONEYCOMB CORE PREPARATION
  - CODED FORM OF INPUT DATA
  - STANDARD SETUP AND RUNTIME HOURS FOR DETAIL LABOR ELEMENTS
  - WEIGHT AND COST OF CORE MATERIAL
- PART CONSOLIDATION
  - CODED FORM OF INPUT DATA
  - STANDARD SETUP AND RUNTIME HOURS FOR DETAIL LABOR ELEMENTS

- FINISHING
  - CODED FORM OF INPUT DATA
  - STANDARD SETUP AND RUNTIME HOURS FOR DETAIL LABOR ELEMENTS
- SUMMARY OF TOTAL FACTORY LABOR STANDARD HOURS
- COST PROJECTIONS
  - CODED FORM OF INPUT DATA
  - UNIT COST ESTIMATE AT SPECIFIED UNIT NUMBER
  - CUMULATIVE COST ESTIMATE AT SPECIFIED UNIT NUMBER
  - CUMULATIVE AVERAGE COST ESTIMATE AT SPECIFIED UNIT NUMBER
  - WEIGHT ESTIMATE OF NET COMPOSITE AND CORE MATERIAL

An overview of the computerized cost estimating system, showing the relationships of its three parts is presented in Figure 5.

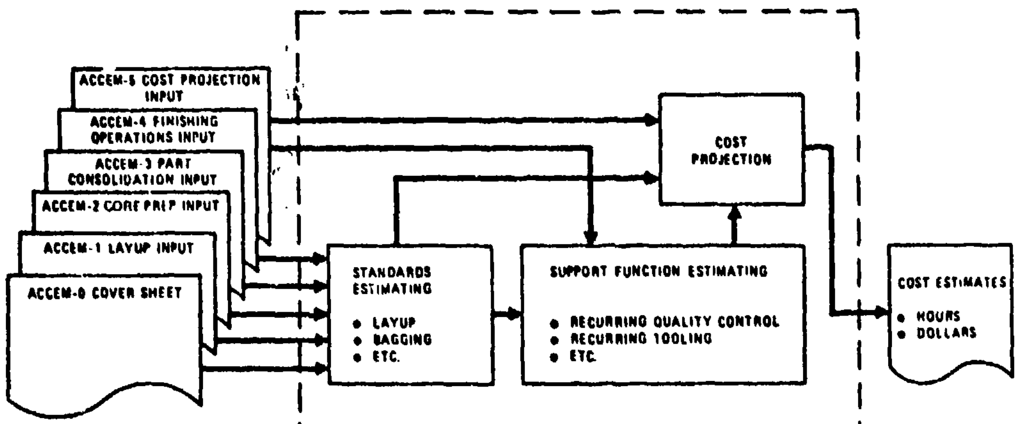


FIGURE 5. COMPUTERIZED COST ESTIMATING SYSTEM

2.0 COMPUTERIZED COST ESTIMATING SYSTEM

The computerized cost estimating system is composed of Inputs, Estimating Methodology, and Outputs.

INPUTS: Six (6) Input Forms have been designed for this system. ACCEM-0 gives general information about the user and the part to be estimated. In addition, this form serves as a checklist that the computer uses to determine the type and quantity of the subsequent input forms submitted by the user. ACCEM-1 (Layup) provides detail information on the part or parts layed up, specifying the layup methods and techniques used and the type and form of advanced composite material layed up. It also provides information on supplementary layup operations such as debulking and trimming as required. ACCEM-2 (Core Operations) describes the processes performed to prepare aluminum honeycomb core according to specifications. ACCEM-3 (Part Consolidation) defines the processes performed in joining and/or curing composite and detail parts. When co-curing, this form identifies the various composite and core elements that are to be cured simultaneously. In addition, this form covers the splicing and bonding of core. More than one curing/joining cycle is available via this form, thereby accomodating pre-curing and secondary bonding operations. ACCEM-4 (Finishing) identifies and provides detail information on the various trimming and drilling operations that are performed on cured composite parts. ACCEM-5 (Cost Projection) specifies the projection factors and rates that are used in calculating final cost estimates.

A detailed description and definition of each input element is presented in Volume II (User's Manual) of this report.

2.1 FACTORY LABOR STANDARDS ESTIMATING

The computerized system estimates the standard hours for the detail elements of layup, core operations, part consolidation, and finishing by solving the appropriate detail industrial Engineering Standards equations using the information provided in the input forms. In this routine, production material costs are also calculated, specifying total usage, and scrap. Weight is calculated by applying the densities of the various material material used to the net material usage (i.e., total usage minus scrap).

This section describes in detail, the fabrication processes covered by this routine. In addition, the detail Industrial Engineering Standards equation for each of these processes are discussed.

Figure 6 illustrates the factory labor standards estimating routine.

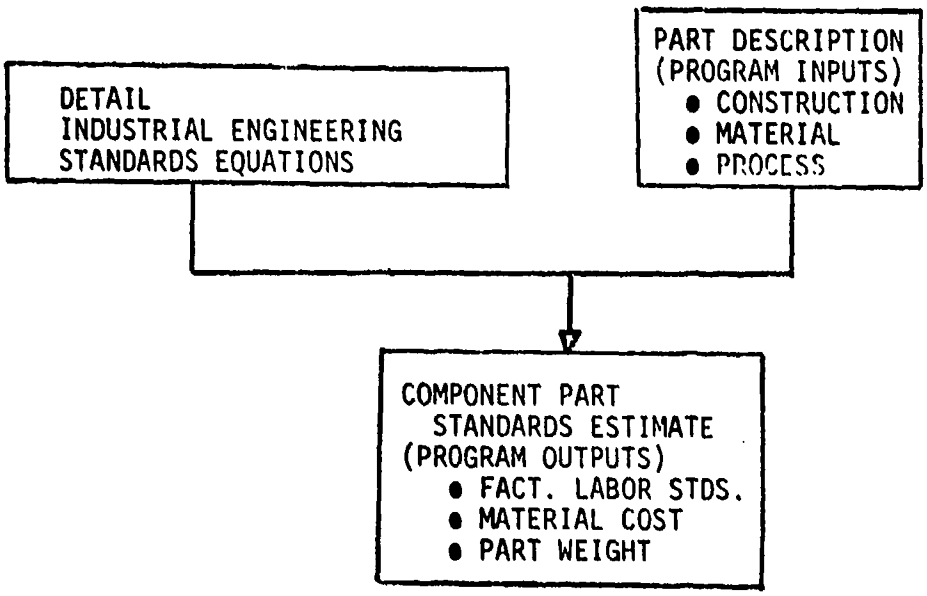


FIGURE 6. FACTORY LABOR STANDARDS ESTIMATING

2.1.1 LAYUP

Layup is the process of depositing advanced composite material on a tool in a predetermined pattern to form a designed part. Layup methods and procedures vary according to part shape, size, number of plies, type of material, etc. In addition, supplementary operations such as debulking and trimming may be performed.

2.1.1.1 LAYUP METHODS

MANUAL LAYUP is the application of composite tape or woven material by hand on a template or tool. This method is most commonly used because of its applicability to any shape or contour using any type or form of composite material. Industrial Engineering Standards have been developed for the hand layup of 3" and 12" wide unidirectional tape and woven cloth (broadgoods).

Figure 7 graphically represents the standards for tape layup. The curves and their corresponding equations define the standard runtime hours to layup one strip of tape of length "L" on a flat surface. The detail operations covered by these equations include: unroll tape on tool, template or preceding ply; smooth down; cut and peel backing paper. Setup time is 0.05 hour.

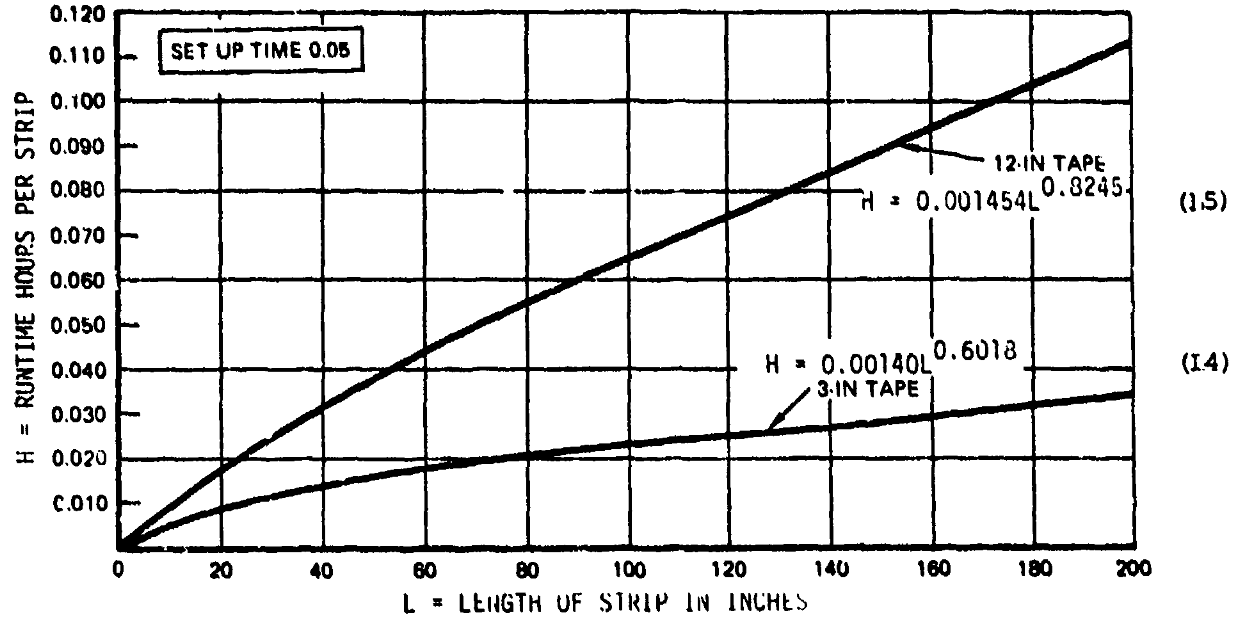
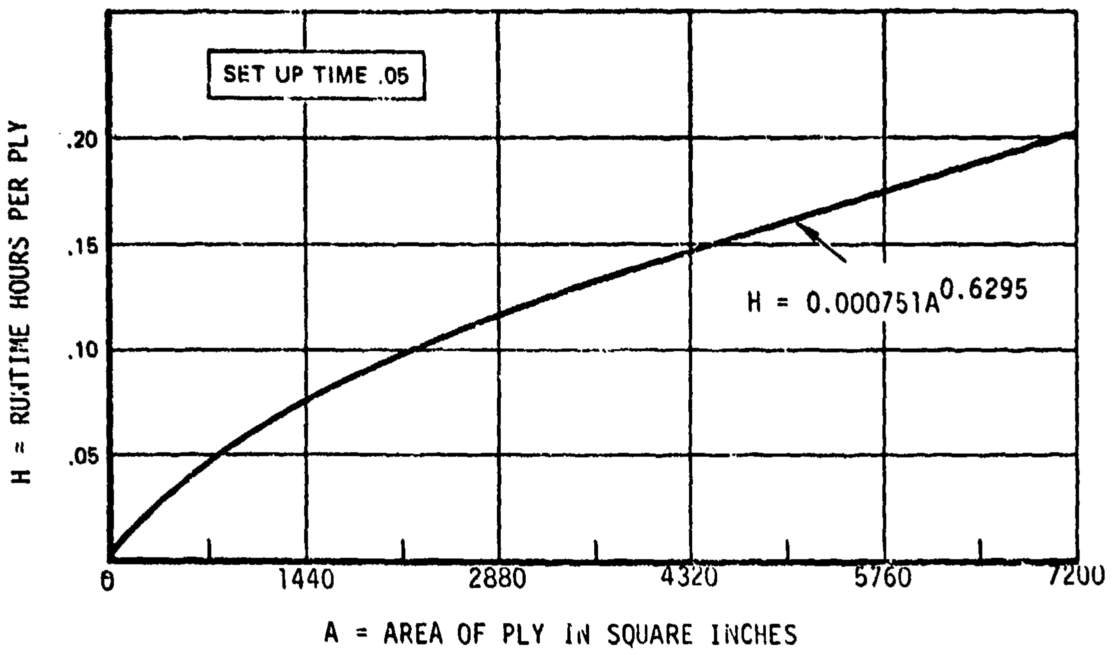


FIGURE 7 STANDARDS EQUATIONS FOR
MANUAL LAYUP OF 3" and 12" UNIDIRECTIONAL TAPE

Standards for the manual layup of woven composite material on flat surfaces were developed through analysis of 44" wide graphite broadgoods. However, the standard equations, shown in Figure 8 are applied to any width of woven material. They define the layup hours per ply in terms of the ply area in square inches. The activities encompassed by this equation are: unroll woven material on layup table, flatten, scribe pattern, position straight edge, cut pattern, move to flat layup tool, and smooth down. Setup time is 0.05 hour.



(L6)

FIGURE 8. STANDARD EQUATION FOR MANUAL LAYUP OF WOVEN MATERIAL

<u>HAND-ASSIST LAYUP</u> uses a machine designed to assist the operator in the placement of advanced composite unidirectional tape. Northrop's hand-assist Flintstone tape layup machine was used in the development of the standards for this layup method. Flintstone lays up 3" and 12" tape on a flat surface only. Spacing is controlled by presetting the transverse movement according to the width of tape used.

The operator moves the tape laying head along the length of the illuminated tape lay-down area. The cutting of strips and removal of backing paper are done manually. The results of the time studies are charted in Figure 9. The standards in Figure 9 cover the following activities: position gantry in start position on template, lay tape by moving dispensing heads along track for required length of strip, cut strip and peel backing paper. Setup time for this operation is 0.10 hour, and among others, covers such activities as mounting roll of tape on reel and threading it through machine.

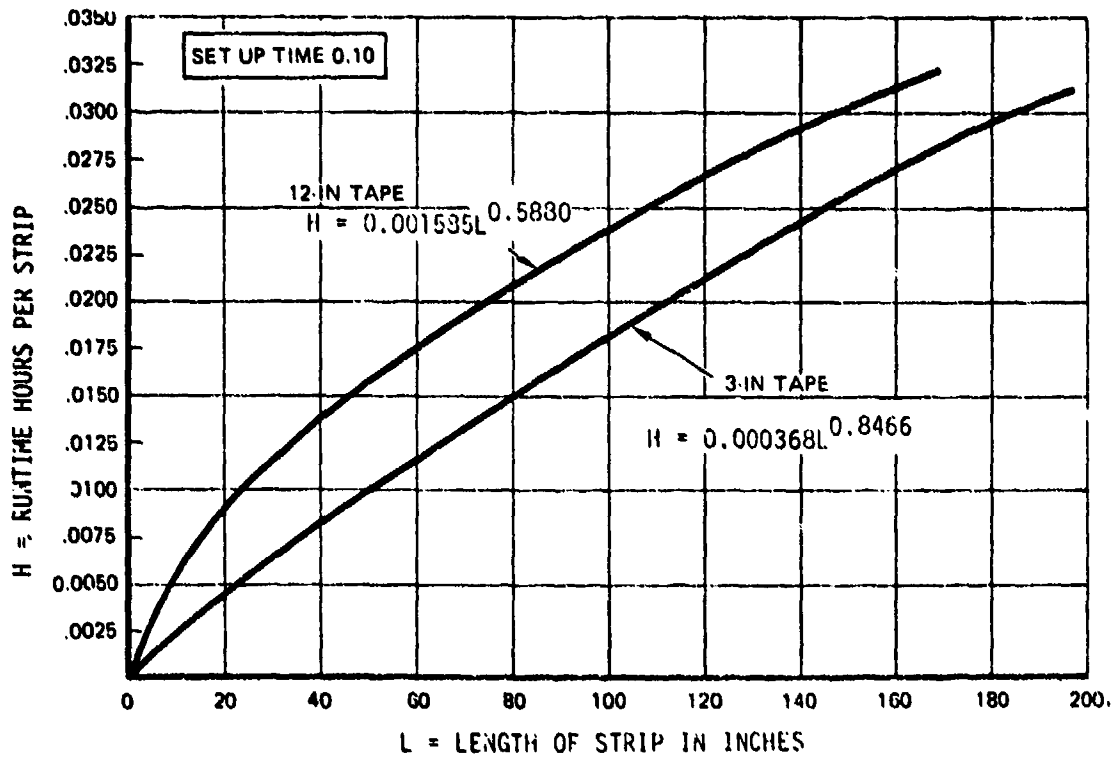


FIGURE 9. STANDARDS EQUATIONS FOR HAND-ASSIST LAYUP USING FLINTSTONE MACHINE

AUTOMATIC LAYUP: The CONRAC automatic tape laying machine was analyzed in this program. This machine is numerically controlled for orientation, spacing and cutting. Removal of backing paper is done automatically through a take-up reel. This machine has two speeds: 360 ipm and 720 ipm. The standards for CONRAC machine layup are shown in Figure 10 . These equations cover layup, cutting and removal of backing paper. Setup time is 0.15 hour and covers loading of tape roll and threading through machine (0.1167 hour per occurrence), and emptying of take-up reel at the end of each roll (0.0167 hour per occurrence).

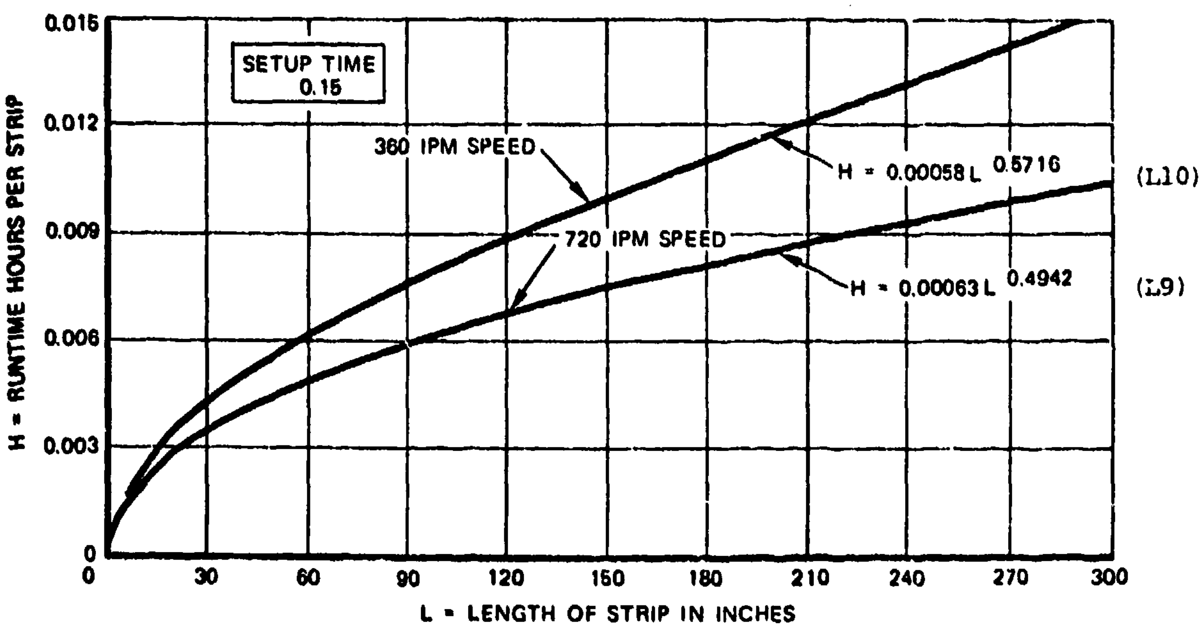


FIGURE 10. STANDARDS EQUATIONS FOR LAYUP USING CONRAC AUTOMATIC TAPE LAYING MACHINE

2.1.1.2 DEPOSITION TECHNIQUES

The procedures followed in laying up composite material vary according to the physical characteristics of the part. The procedures covered by this program are "ply-on-ply" and "ply-on-mylar".

PLY-ON-PLY When composite strips are layed up directly on tape of a previously layed up ply, the procedure is called ply-on-ply layup, as illustrated in Figure 11.

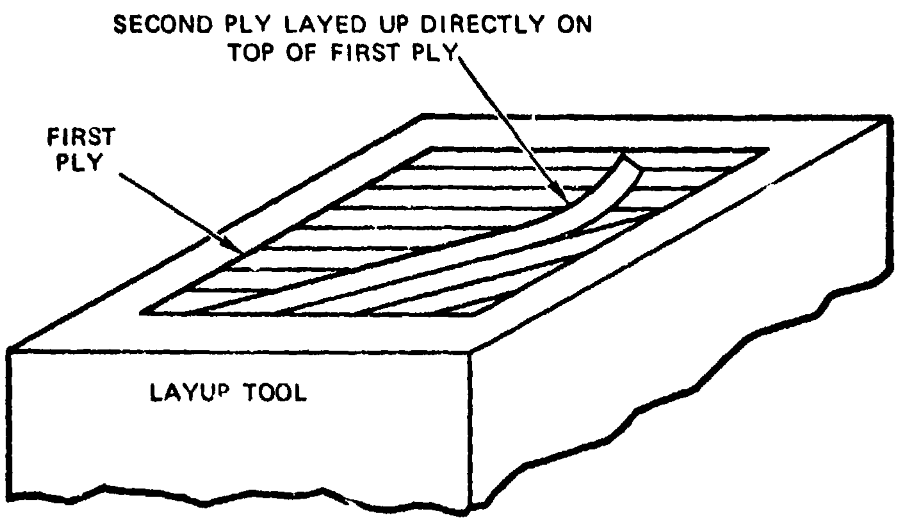


FIGURE 11. PLY-ON-PLY LAYUP

PLY-ON-MYLAR When each ply is first layed up on an individual template, then stacked to form the part, the procedure is called ply-on-mylar layup. Figure 12 illustrates this procedure.

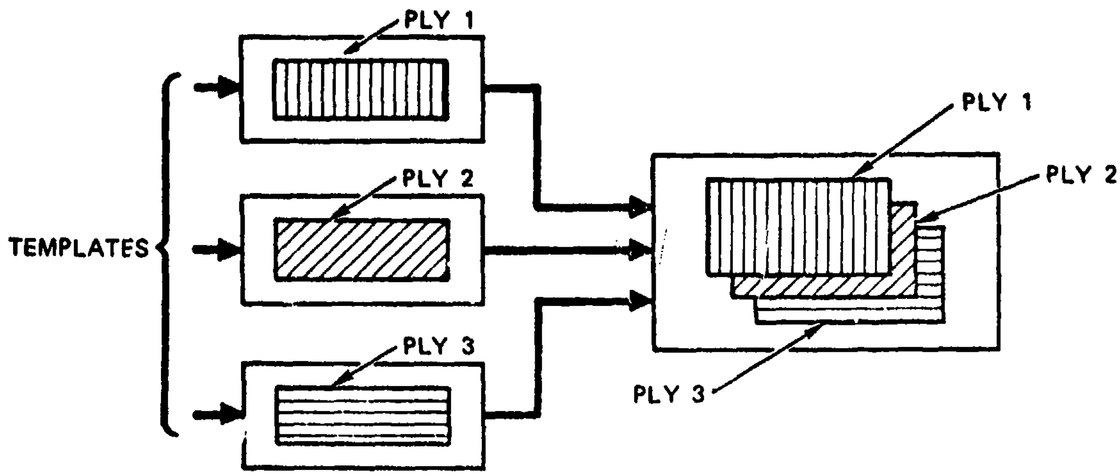


FIGURE 12. PLY-ON-MYLAR LAYUP

Standards for template handling represents the time required to position and tape down the template.

$$H = 0.000107A^{0.7701} \quad (L3)$$

WHERE:

H = Runtime hours per template

A = Area of ply, in square inches

Total template handling time is obtained by multiplying the results of this equation by the number of occurrences.

Standards for transferring each layed up ply from the template to the stack or layup tool are as follows:

$$H = 0.000145A^{0.6711}, \tag{L11}$$

WHERE:

H = Runtime hours per transfer

A = Area of ply, in square inches

Total transfer time is obtained by multiplying the results of this equations by the number of plies layed up.

2.1.1.3 HANDLING METHODS

PRE-PLYING When plies are layed up on a flat surface (using either ply-on-ply or ply-on-mylar technique) to form a stack of plies and then transferred to the layup tool as a group, this techniques is called preplying (see Figure 13). Preplying is commonly used when forming slight contours of minimal thickness, or when tapered plies are to be layed up.

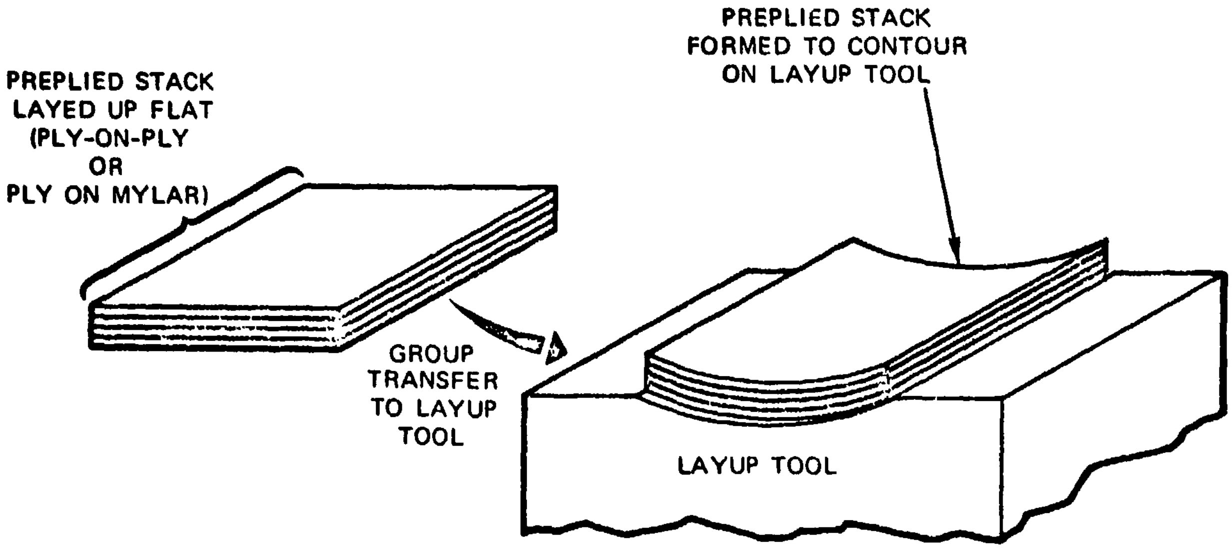


FIGURE 13. PRE-PLYING

The additional time required to transfer each pre-plied stack to the layup tool is calculated by the following equation:

$$H = 0.000145A^{0.6711}, \qquad \text{(L12)}$$

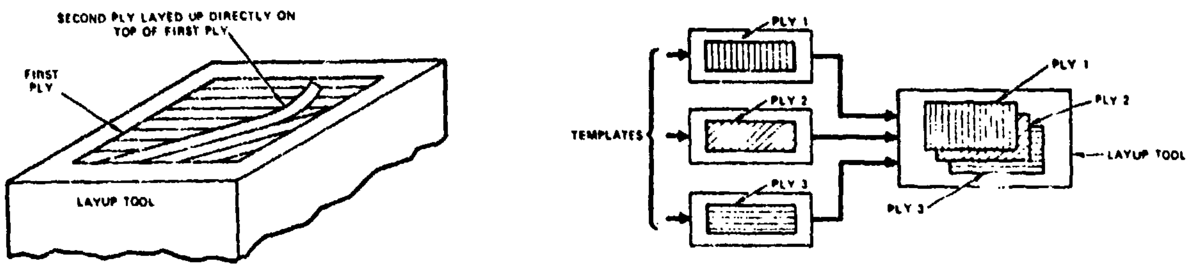
WHERE:

H = Runtime hours per transfer

A = Area of stack, in square inches

Total transfer time is obtained by multiplying the results of this equation by the number of preplied stacks layed up.

DIRECT-ON-TOOL When the first ply is layed up directly on the layup tool and subsequent plies are layed up on the preceding ply, the procedure is called "direct-on-tool" layup. This may be accomplished using either ply-on-ply or ply-on-mylar deposition technique as illustrated in Figure 14.



PLY-ON-PLY PLY-ON-MYLAR

FIGURE 14. DIRECT-ON-TOOL LAYUP

2.1.1.4 LAYUP COMPLEXITY

The cost estimating system contains factors and equations that quantify the layup complexity of a composite part. This complexity, defined in terms of bends, is measured by the amount of additional effort required to form the part to its required shape during the layup process. Bends have been classified under two major categories: Straight Bends and Curved Bends. Straight bends have bend lines that follow a straight line pattern. They may be sharp (abrupt change in ply plane direction) or radial (gradual change in ply plane direction, i.e., having a radius of curvature). In addition, straight bends may be described as male (layed up on a male tool) or female (layed up on a female tool). Curved bends have bend lines that follow a

curved pattern. They cause either a shrink or stretch condition in the part flanges. Figures 15 and 16 illustrate these different types of bends. The hours associated with each type of bend were derived through a detailed analysis of data collected from actual observation of layup operations. When laying up on bends, extra effort is required to smooth down plies along the bend line. The amount of extra effort required varies for each type of bend and is generally a function of bend length and, when applicable, radius of curvature and flange width. As an example, smoothing down a ply layed up on a male tool along a straight bend simply involves the application of pressure along the exposed bendline. For curved bends, however, pre-heating, cutting of gores or darts and/or stretching of plies might be necessary to obtain the desired part shape. These degrees of complexities have been quantified and are presented in the Summary of Layup Standards. A more comprehensive analysis of curved bends is presented in Volume III.

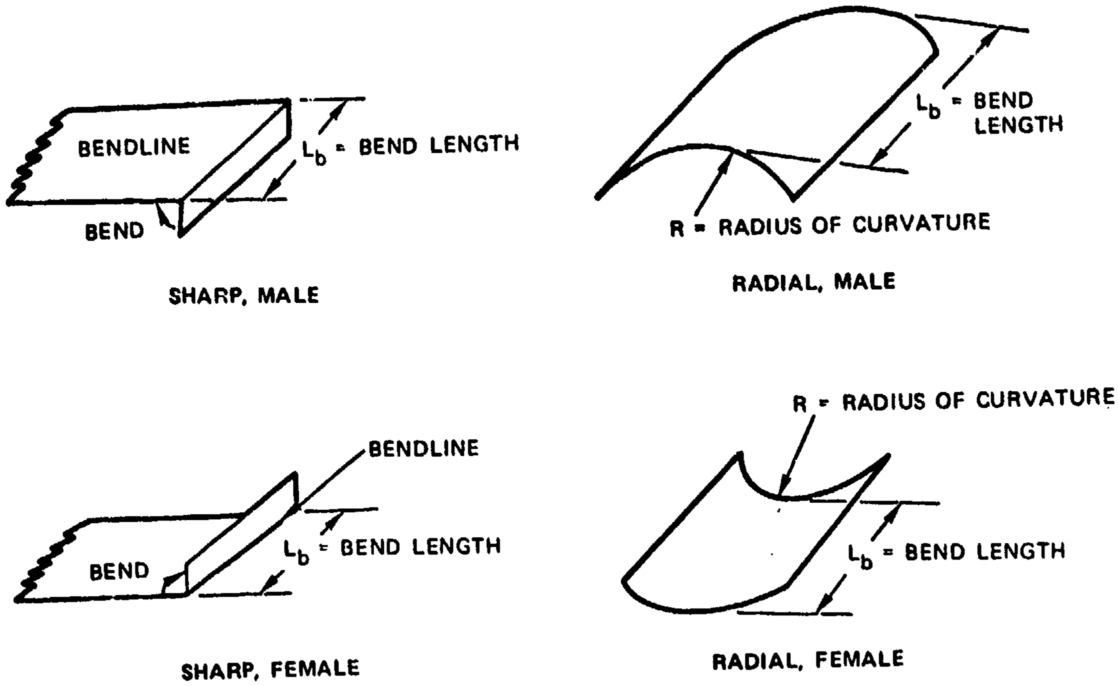


FIGURE 15. STRAIGHT BENDS

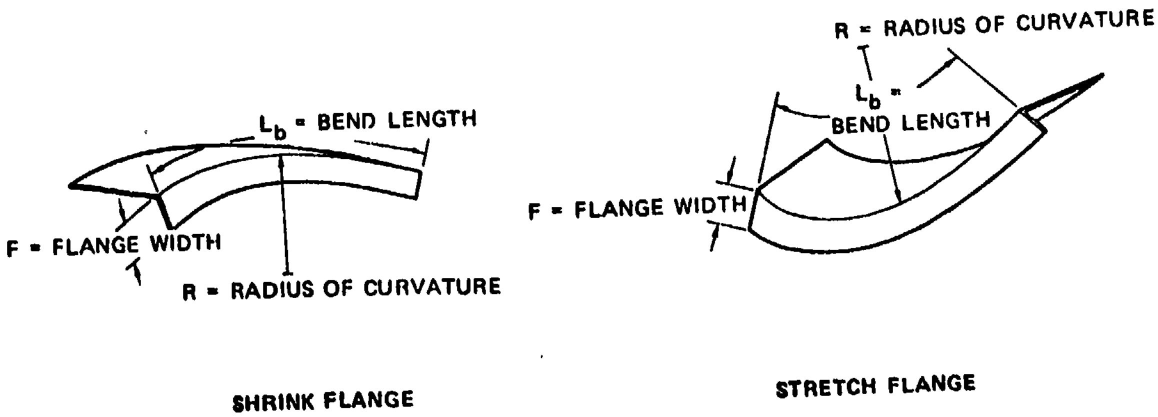
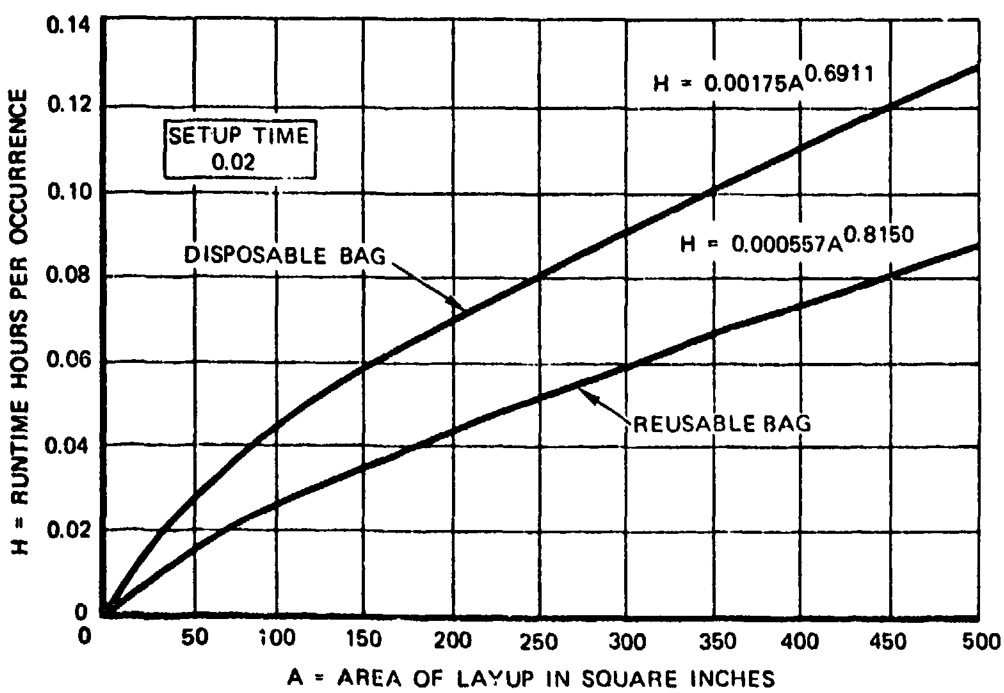


FIGURE 16. CURVED BENDS

2.1.1.5 DEBULKING

When a large number of plies is to be layed up, debulking is performed after every 10 to 12 plies, or as specified. Debulking is the process of densifying plies during layup and is usually accomplished through the application of vacuum pressure to a stack of plies enclosed in a vacuum bag. The bag used may be reusable or disposable.

The standards equations for debulking are presented in Figure 17. The equations include the application and removal of release agent, vent cloth, and vacuum bag; sealing or clamping the edges; and application of vacuum. Setup time is 0.02 hour.



(L16)

(L17)

FIGURE 17. STANDARDS EQUATION FOR DEBULKING

2.1.1.6 TRIMMING OF PRECURED LAYUP

Layed up plies are usually trimmed to net size or near net size after layup, to minimize machining operations after cure. The standard equation for trimming by hand using a sharp-edged tool is as follows:

$$H = 0.00011P, \qquad \text{(L18)}$$

WHERE:

H = Runtime hours per part

P = Perimeter of part, in inches

2.1.1.7 SUMMARY OF LAYUP STANDARDS

BASIC DEPOSITION

DETAIL ELEMENTS	SETUP	RUNTIME	
CLEAN LAYUP TOOL SURFACE		$0.000006A$	(L1)
APPLY RELEASE AGENT TO LAYUP TOOL SURFACE		$0.000009A$	(L2)
POSITION TEMPLATE (MYLAR) ON TABLE AND TAPE DOWN		$0.000107A^{0.77006}$	(L3)
PLY DEPOSITION			
MANUAL - 3" TAPE	0.05	$0.00140L^{0.6018}$	(L4)
- 12" TAPE	0.05	$0.001454L^{0.8245}$	(L5)
- WOVEN MATERIAL	0.05	$0.000751A^{0.6295}$	(L6)
HAND-ASSIST - 3" TAPE	0.10	$0.000368L^{0.8446}$	(L7)
- 12" TAPE	0.10	$0.001585L^{0.5580}$	(L8)
CONRAC AUTO. (720 IPM)	0.15	$0.00063L^{0.4942}$	(L9)
(360 IPM)	0.15	$0.00058L^{0.5716}$	(L10)
TRANSFER PLY FROM TEMPLATE TO STACK OR LAYUP TOOL		$0.000145A^{0.6711}$	(L11)
TRANSFER STACK TO LAYUP TOOL		$0.000145A^{0.6711}$	(L12)
CLEAN CURING TOOL SURFACE		$0.000006A$	(L13)
APPLY RELEASE AGENT TO CURING TOOL SURFACE		$0.000009A$	(L14)
TRANSFER LAYUP TO CURING TOOL		$0.000145A^{0.6711}$	(L15)

WHERE:

A = Area of ply, or greatest ply area of stack or layup, in square inches

L = Length of ply strip, in inches

LAYUP COMPLEXITY INCREMENTS

BEND TYPE	BEND FACTORS	NOTES	
STRAIGHT BENDS			
SHARP, MALE	$0.00007L_b$		(B1)
SHARP, FEMALE	$0.00016L_b$		(B2)
RADIAL, MALE	$0.00007L_b$	WHEN $R \le 2"$	(B3a)
	NO FACTOR APPLIED	WHEN $R > 2"$	(B3b)
RADIAL, FEMALE	$0.00016L_b$	WHEN $R \le 2"$	(B4a)
	$[0.00047R^{-1.3585}]L_b$	When $R > 2"$	(B4b)
CURVED BENDS			
TAPE			
STRETCH FLANGE	$[0.015R^{-.5532}F^{.7456}]L_b$		(B5)
SHRINK FLANGE	$[0.0064R^{-.5379}F^{.5178}]L_b$		(B6)
WOVEN	$[0.00444R^{-0.5958} + 0.0007]L_b$		(B7)

WHERE: L_b = Length of bendline
R = Radius of curvature
F = Flange Width

NOTE: The additional increment of runtime is added as follows:

Ply-On-Ply/Direct-On-Tool	(L4) - (L6)	Ply Deposition
Ply-On-Ply/Pre-Plying	(L12)	Transfer Stack to Layup Tool
Ply-On-Mylar/Direct-On-Tool	(L11)	Transfer Ply to Layup Tool
Ply-On-Mylar/Pre-Plying	(L2)	Transfer stack to Layup Tool

SUPPLEMENTARY LAYUP OPERATIONS

DETAIL ELEMENTS	SETUP	RUNTIME	
DEBULKING			
DISPOSABLE BAG	0.02	$0.00175A^{0.6911}$	(L16)
REUSABLE BAG	0.02	$0.000557A^{0.8150}$	(L17)
TRIMMING		$0.00011P$	(L18)

WHERE:

A = Area of layup, in square inches

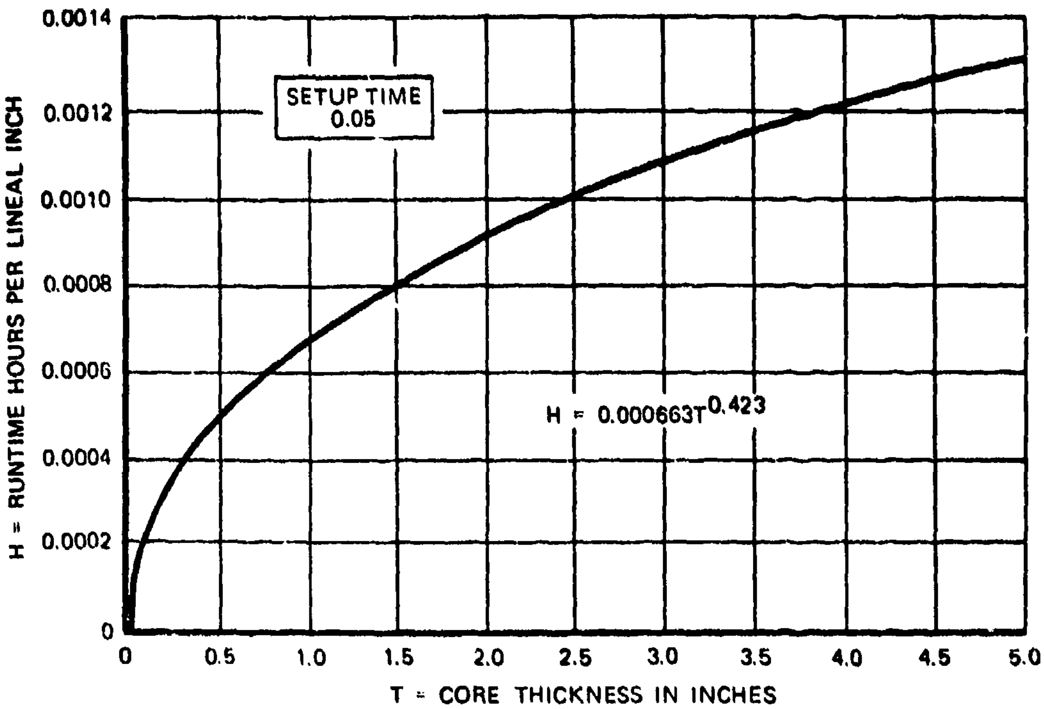
P = Perimeter of layup, in inches

2.1.2 ALUMINUM HONEYCOMB CORE PREPARATION

Aluminum honeycomb core preparation involves all the operations required to transform the raw stock to its final dimensional specifications. These operations include: sawing, machining, forming, and stabilization. Standards for core operations were derived from Northrop's long experience with honeycomb core, and have been continually updated to incorporate new processing methods, tools, equipment, etc. The detail standards for each operation are discussed below.

2.1.2.1 SAWING

This operation is required to saw appropriate part configuration out of vendor supplied standard size raw stock. This procedure is accomplished by placing raw stock on the band or radial arm saw, position and saw it to required dimensional specifications.



(H2)

FIGURE 18. STANDARDS EQUATION FOR CORE SAWING

The equation for sawing as shown in Figure 18 represents standard hours per lineal inch to saw the core as related to core thickness. Sawing runtime is calculated by multiplying the results of this equation by the length of the cut. The handling time equation which accounts for the handling of the core before, during, and after the sawing operations is as follows:

$$H = 0.000453A^{0.3810}, \qquad \text{(H1)}$$

WHERE:

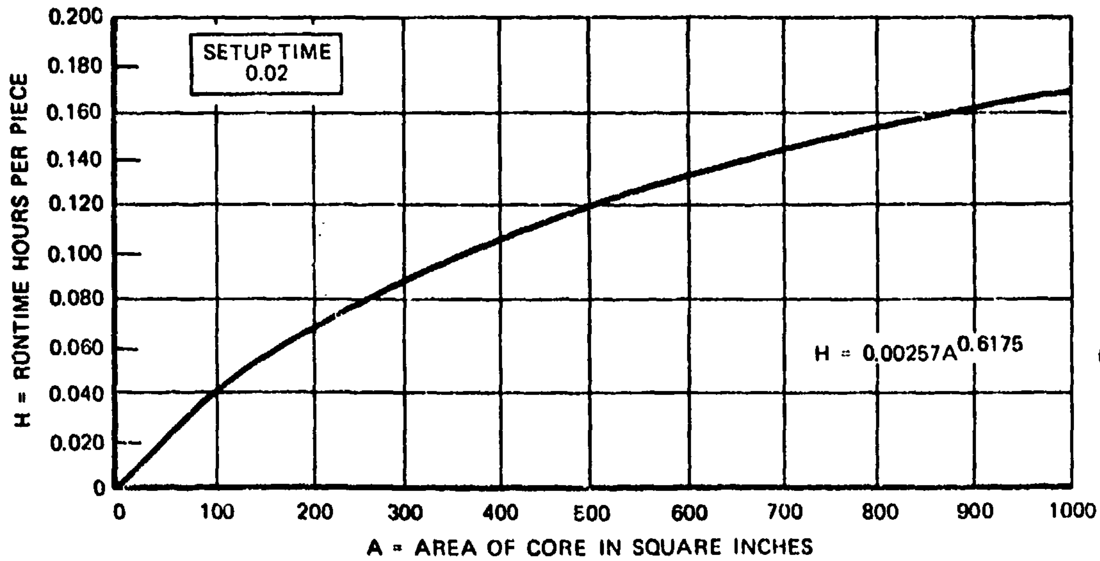
H = Runtime hours per part

A = Area of core, in square inches

Summing the results of these calculations will give the total standard hours for sawing.

2.1.2.2 MACHINING

POLYGLYCOL APPLICATIONS: Polyglycol is a chemical compound which is applied to the cells of the aluminum honeycomb core to hold it rigidly in the tool fixture, and to prevent the collapsing or crushing of the cells during the various machining operations. Solid chips of polyglycol are melted, and then poured into the core which is positioned on a heated chuck plate or tool fixture. After all machining operations are completed, polyglycol is removed from the core cells by immersion in a hot water bath. The graph in Figure 19 represents the standard hours to fill and remove the polyglycol.



(H3)

FIGURE 19. STANDARDS EQUATION FOR POLYGLYCOL APPLICATION

MACHINING: Machining operations are performed to bring core into its final dimensional specifications. There are numerous ways of machining core. Those analyzed in this program include: flat and contour machining, end mill machining, and cut outs. These operations and their associated standards are discussed below.

The handling time for these operations which represents hours per piece to load and unload the core is expressed as:

$$H = 0.002657A^{0.5051} \qquad \text{(H4)}$$

WHERE:

H = Runtime hours per part

A = Core area in square inches

Flat machining is the process of machining the exposed surface of the aluminum core parallel to the machine bed, the standards equation for this operation define total runtime in terms of the maximum width and average length of the cut, (utilizing a 3" cutter) and the cutting rate. To determine the machine time the following formula is used:

$$H = \frac{W}{1.5}(L + 6)(.0002) \qquad \text{(H5)}$$

WHERE:

H = Runtime hours per part

W = Maximum surface width, in inches

L = Average length of pass, in inches

6 = Overrun of 3" at each end of pass

0.0002 = Cutting time per lineal inch

Setup time = 0.050 Hour

Total runtime hours is obtained by summing the results of the machine time and handling time equations.

Contour machining is the process by which the exposed core surface is machined to a contour as exhibited in Figure 20. The cutter makes passes along the percent line of the part following the contour established by the guide bars of the machine. The depth of the cut for this operation is .250 inch per pass with a 1" valve cutter. The standards for this operation are a function of the surface contour width, average length, and the cutting rate. This standard applies to both rough and finish cuts.

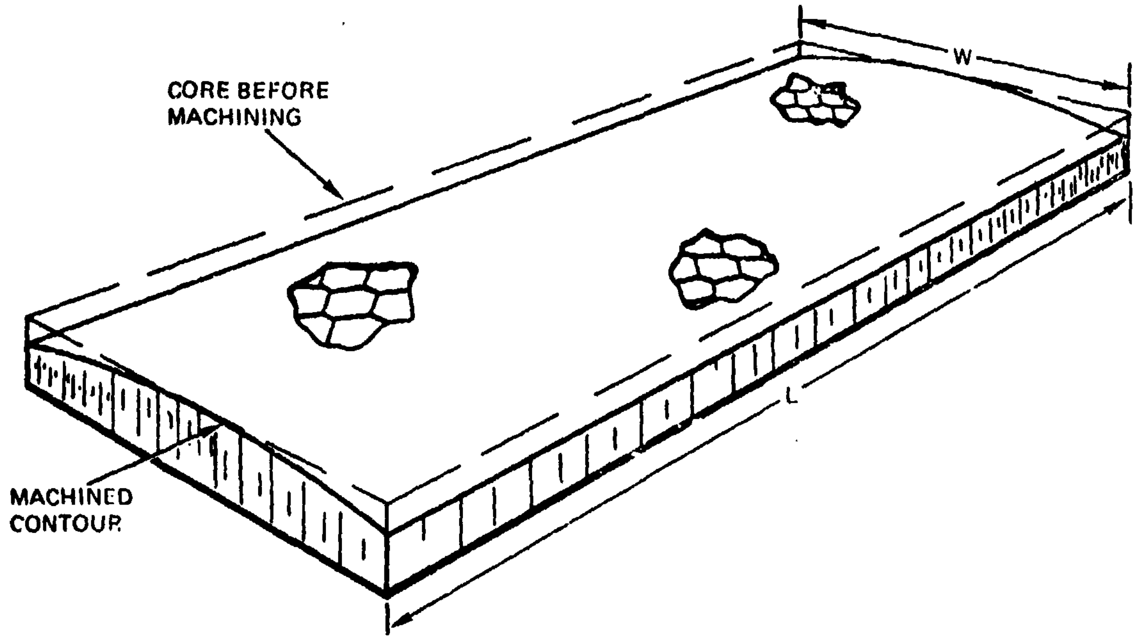


FIGURE 20. CONTOUR MACHINED CORE

To determine the machine time for contour cuts, the following formula is used.

$$H = 4W\ (L + 6)(.00005) \qquad \text{(H6)}$$

WHERE:

H = Runtime hours per part

W = Maximum surface contour width, in inches

L = Average length of pass, in inches

6 = Overrun of 3" at each end of pass

0.00005 = Cutting rate per lineal inch

Total runtime hours is obtained by summing the results of the machine time and handling time equations.

END MILL MACHINING: The use of an end mill allows many different types of machine operations to be performed. A step cut is made perpendicular to the core surface, whereas a scarf cut is angular. Blending is the process of machining the mated surfaces of core and structural members (see Figure 21). The standards for these operations are dependent on the width and length of the cut to be made.

To determine the machine time the following formula is used:

STEP AND SCARF

$$H = 0.0006L, \text{ for cutting width } \leq 1 \text{ inch} \qquad \text{(H7)}$$

$$H = 0.0006A, \text{ for cutting width } > 1 \text{ inch} \qquad \text{(H8)}$$

BLENDING

$$H = 0.0009L \qquad \text{(H9)}$$

WHERE:

H = Runtime hours per cut

L = Length of cut, in inches

A = Area of cut, in square inches

Setup time is 0.11 Hour.

Total runtime is obtained by summing the results of the machine time and handling time equations.

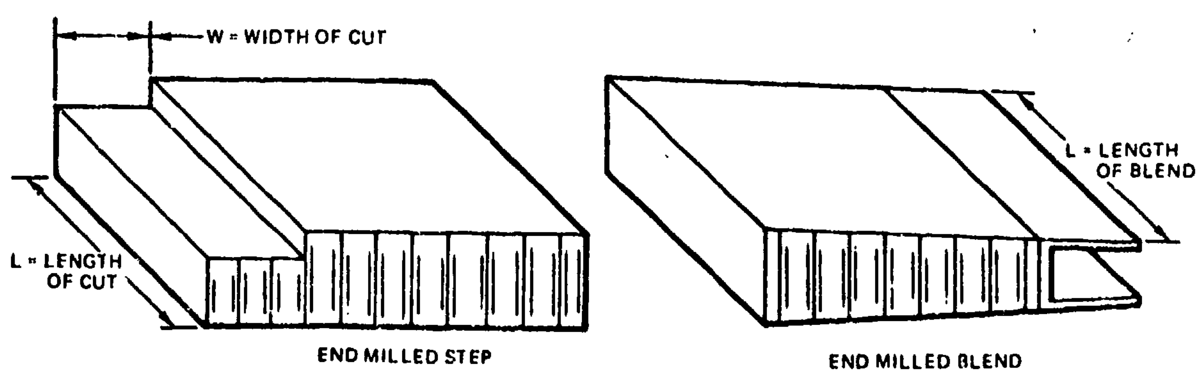


FIGURE 21. END MILL CUTS OF CORE

CORE CUTOUTS: This operation is used when holes or slots are required in the core. This is accomplished after the polyglycol has been removed and the aluminum core is free of the fixture. Cutouts are made using hand tools and guided by a template.

To determine the runtime the following formula is used:

$$H = .0120N \qquad \text{(H10)}$$

WHERE:

H = Standard runtime hours

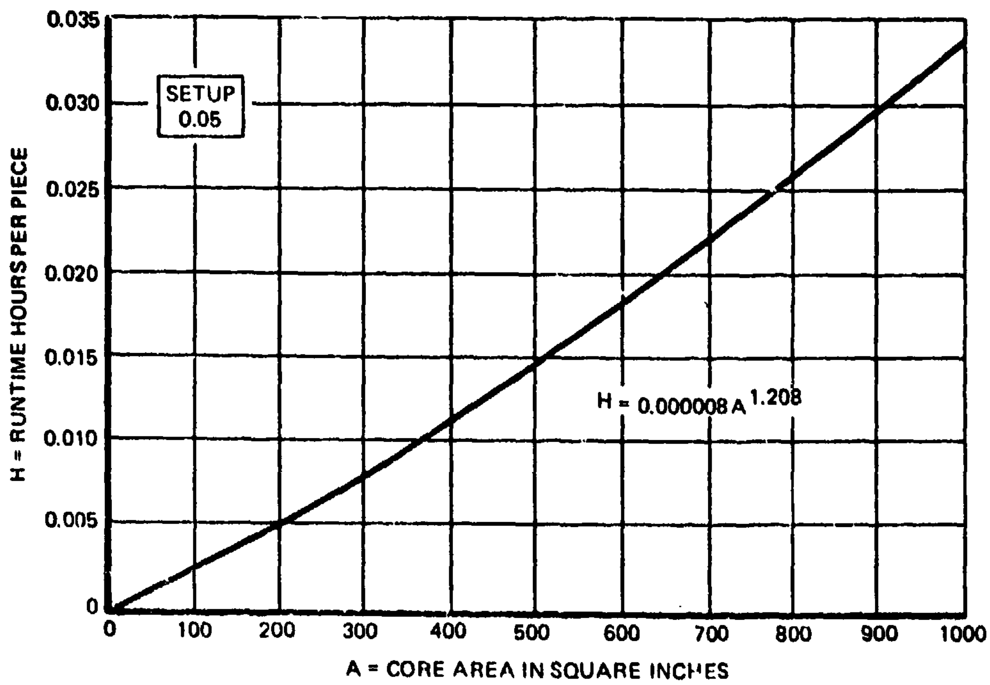
N = Number of cutouts

Setup time = 0.01 Hour.

2.1.2.3 FORMING

Forming is the process of bending the core to desired contour. It may be accomplished by hand or power brake.

HAND FORMING: This is the method of shaping the core against contoured tools utilizing rubber rollers. Gradual contours and curvatures are formed using this method. The equation for hand forming of the core, shown graphically in Figure 22 relates runtime hours to core area.



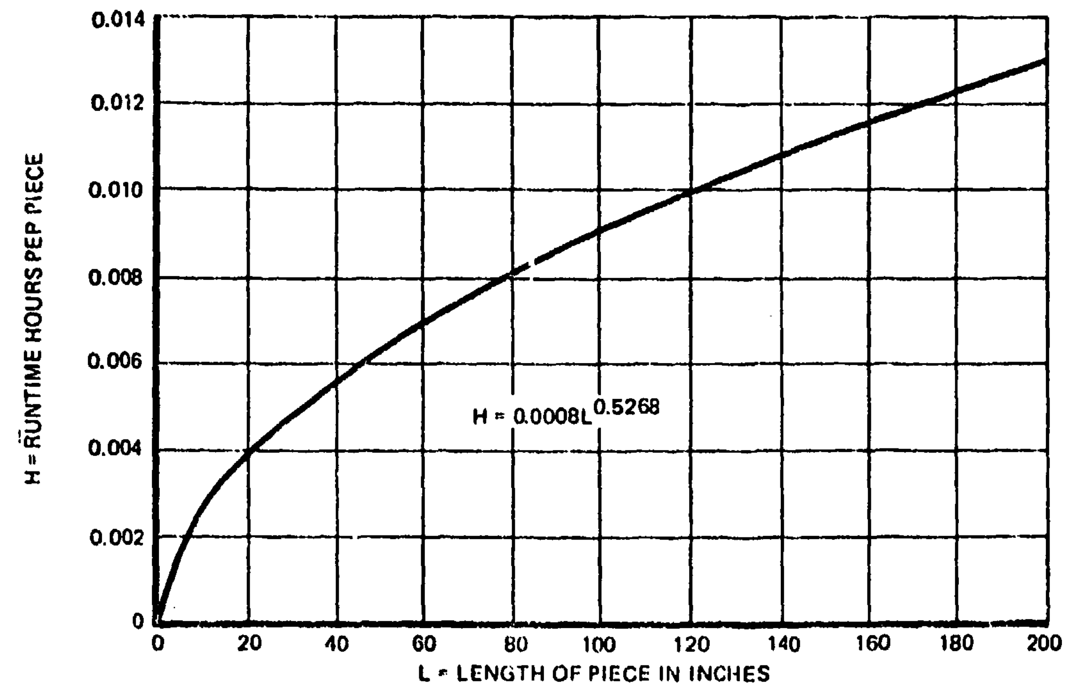
(H11)

FIGURE 22. STANDARDS EQUATION FOR HAND FORMING CORE

POWER BRAKE FORMING: If a sharp radius or compound contours are required, then a power brake is used to form the aluminum core. In order to prevent the crushing or damaging of the core cells during this operation, the core is placed between two aluminum sheets before the core is hit by the power brake.

The standards for the brake forming operation (Figure 23) represents an operating time (includes handling of core) per part. For varying cell sizes, additional increments of brake forming time are to be added, per inch of radius of curvature.

Setup Time	=	0.15 Hour, if die length $\leq$ 5 feet
	=	0.19 Hour, if die length $>$ 6 feet
Add		0.12 Hour per die change
Add		0.03 Hour per die reposition



(H12)

FIGURE 23. STANDARDS EQUATION FOR BRAKE FORMING CORE

Additional incremental brake forming runtime:

$$H = 0.0091R, \text{ if } C = 0.1250 \qquad \text{(H12a)}$$

$$H = 0.0065R, \text{ if } C = 0.1875 \qquad \text{(H12b)}$$

$$H = 0.0052R, \text{ if } C = 0.2500 \qquad \text{(H12c)}$$

$$H = 0.0039R, \text{ if } C = 0.3125 \qquad \text{(H12d)}$$

WHERE:

H = Runtime hour increment per part

R = Radius of curvature, in inches

C = Cell size, in inches

Total runtime hours are obtained by adding the operating time and the additional incremental brake forming time.

2.1.2.4 STABILIZATION

Stabilization is the strengthening of localized areas of honeycomb core by filling the cells with chemical agents. The two methods of stabilization are liquid potting and tape foaming. Potting is accomplished by pouring liquid into the core cells. The standards for liquid potting encompasses the time to obtain ingredients, weigh and mix, positioning of the core, and the pouri and brushing of the potting liquid into the cells. The liquid potting standards equation is as follows:

$$H = 0.0105V \qquad \text{(H13)}$$

WHERE:

H = Standard runtime hours per part

V = Vol... of area to be potted, in cubic inches

Setup Time = 0.05 Hour

Tape foaming is the process by which a tape adhesive is pressed into the core cells from both sides, until the area is filled. The standard for tape foaming represents the time to obtain tape, cut to required length and width and position tape on core. Heat is then applied to soften the tape prior to pressing into the core cells. Tape foaming standards equation is as follows:

$$H = 0.0257V \qquad \text{(H14)}$$

WHERE:

H = Standard runtime hours per part
V = Volume of area to be foamed, in cubic inches

Setup Time = 0.05 Hour.

2.1.2.5 CLEANING

After the core has been machined and formed, it is cleaned by immersion in a chemical bath. The standards equation for cleaning covers the time to immerse and remove the core in the bath.

$$H = 0.00046V^{0.4257} \qquad \text{(H15)}$$

WHERE:

H = Standard runtime hours per part
V = Volume of core, in cubic inches

Setup Time = 0.05 Hour.

2.1.2.5 SUMMARY OF CORE PREPARATION STANDARDS ESTIMATING RELATIONSHIPS

DETAIL ELEMENT	SETUP	RUNTIME	
SAWING			
HANDLING		$H = 0.000453A^{0.3810}$	(H1)
SAWING	0.05	$H = (0.000663T^{0.4230})L$	(H2)
MACHINING			
POLYGLYCOL	0.02	$H = 0.00257A^{0.6175}$	(H3)
HANDLING		$H = 0.002657A^{0.5051}$	(H4)
FLAT	0.50	$H = 0.0002(W/1.5)(L+6)$	(H5)
CONTOUR	0.60	$H = 0.00005(4W)(L+6)$	(H6)
END MILL STEP	0.11	$H = 0.0006WL$	(H7)
END MILL SCARF	0.11	$H = 0.0006WL$	(H8)
END MILL BLEND	0.11	$H = 0.0009L$	(H9)
CUTOUT	0.01	$H = 0.0120(N)$	(H10)
FORMING			
HAND	0.05	$H = 0.000008A^{1.208}$	(H11)
POWER BRAKE		$H = 0.0008L^{0.5268}$	(H12)
SETUP			
IF DIE LENGTH ≤ 6 FT.	0.15		
IF DIE LENGTH > 6 FT.	0.19		
PER DIE CHANGE	0.12		
PER DIE REPOSITION	0.03		
INCREMENTS			
IF C = 0.1250 IN.		$H = 0.0091R$	(H12a)
IF C = 0.1875 IN.		$H = 0.0065R$	(H12b)
IF C = 0.2500 IN.		$H = 0.0052R$	(H12c)
IF C ≤ 0.3125 IN.		$H = 0.0039R$	(H12d)
LIQUID POTTING	0.05	$H = 0.0105V$	(H13)
TAPE FOAMING	0.05	$H = 0.0257V$	(H14)
CLEANING	0.05	$H = 0.00046V^{0.4257}$	(H15)

WHERE:

A = Core area in square inches
T = Core thickness, in inches
L = Length of cut, in inches
W = Maximum width of cut, in inches
N = Number of cutouts
R = Radius of curvature to be formed, in inches
C = Cell size, in inches
V = Volume to be potted or foamed, in inches

2.1.3 PART CONSOLIDATION

Part consolidation refers to the processes involved in joining detail elements and/or curing composite material. The joining operations include splicing and bonding. The curing processes include vacuum bag/autoclave cure, vacuum bag/oven cure, and thermal expansion molding.

2.1.3.1 JOINING DETAIL ELEMENTS

Two consolidation operations in which an adhesive is used to join detail elements are splicing and bonding. Splicing is the edgewise joining of two or more pieces of core. Bonding is the process in which the element surfaces are adhered. The standards equation for applying the adhesive relates run-time to adhesive application area. In order to complete the consolidation cycle, the part which results from the joining of elements may be cured using one of the processes discussed in the following sections (complete lists of standards elements are presented in the Summary), or it may be cured by heating with a hand gun. For the latter method, a standards equation has been developed for handling time which represents time to gather details, prefit, assemble the details after adhesive application, and apply heat. Total run-time is the sum of the handling and adhesive application equations.

HANDLING (C1)

$$H = 0.0015A^{0.6311}$$

ADHESIVE APPLICATION (C2)

$$H = 0.000055A_a$$

WHERE:

H = Runtime hours per part

A = Core area, in square inches

A_a = Adhesive application area, in square inches

Setup Time = 0.05 Hour.

2.1.3.2 CURING PROCESS

Curing is accomplished through the application of pressure and heat to advanced composite material. There are several ways of curing, as shown below.

CURING PROCESSES

PRESSURE	HEAT	NOTES
Vacuum Bagging & Autoclave	Autoclave	Curing over 15 psi
Vacuum Bagging	Oven	Curing at or below 15 psi
Thermal Expansion Molds	Oven	Heat by convection
Thermal Expansion Molds	Heating Element	Heat by conduction

The detail elements of each process and their corresponding equations are presented in the Summary.

VACUUM BAG/AUTOCLAVE CURE: Vacuum bagging is the process of applying full vacuum pressure (15 psi) to layed up advanced composite material. This process is accomplished by containing the material in a bag and applying vacuum pressure via a vacuum pump.

Two types of bag material are used: disposable bags and reusable bags. Disposable bags are material that need to be replaced after every curing operation. Disposable bags are sealed to the curing tool by the application of zinc chromate sealing tape along the bag periphery. Reusable bags are made of silicone or butyl rubber and are custom fitted to the part it envelopes. Sealing to the curing tool is accomplished by clamping around the edges. These bags are initially more expensive than disposable bags, but are cost competitive in the long run because they are reusable and repairable.

When advanced composite materials are to be cured at pressures higher than that provided by vacuum bagging (15 psi), an autoclave is used. The autoclave provides the additional pressure as well as temperature required to cure a composite part.

VACUUM BAG/OVEN CURE: When composite material is to be cured at vacuum bag pressure (15 psi), the bagged material is heated in an oven (a vessel that provides heat by convection). The bagging procedures for oven curing are similar to bagging for autoclave cure.

THERMAL EXPANSION MOLDING: An alternative to vacuum bagging is the use of thermal expansion molds (elastomeric tools). Thermal expansion molding is the process of curing advanced composite material by the application of heat to encased expandable rubber molds that contain the layed up material. Heat is transferred to the mold cage (and to the composite material) by convection in an oven or by conduction from a heating element. The rubber molds expand as heat is absorbed. This expansion causes the required pressure to be applied on the material.

2.1.3.3 SUMMARY OF PART CONSOLIDATION STANDARDS ESTIMATING RELATIONSHIPS

SPLICING/BONDING

DETAIL ELEMENT	SETUP	RUNTIME	
APPLY ADHESIVE	0.05	$0.000055A_a$	(C1)
HANDLING		$0.0015A^{0.6311}$	(C2)

WHERE:

A_a = Adhesive application area, in square inches

A = Part area, in square inches

NOTE: These standards are applicable only if the adhesive which joins the detail elements is cured by applying heat with a hand gun.

VACUUM BAG/AUTOCLAVE CURE

DETAIL ELEMENT	SETUP	RUNTIME	APPLICATION DISP.	APPLICATION REUS.	
SETUP	0.07				
GATHER DETAILS, PREFIT, DISASSEMBLE AND CLEAN		$0.001326\ (A^{0.5252})$	X	X	(V1)
APPLY ADHESIVE		$0.000055[A_a]$	X	X	(V2)
ASSEMBLE DETAIL PARTS		$0.000145\ (A^{0.6711})$	X	X	(V3)
APPLY POROUS SEPARATOR FILM		$0.000009A_b$	X	X	(V4)
APPLY BLEEDER PLIES		$0.00002A_r$	X	X	(V5)
APPLY NON-POROUS SEPARATOR FILM		$0.000009A_b$	X	X	(V6)
APPLY VENT CLOTH		$0.00002A_b$	X	X	(V7)
INSTALL VACUUM FITTINGS		$0.0062N_f$	X		(V8)
INSTALL THERMOCOUPLES		$0.0162N_f$	X	X	(V9)
APPLY SEAL STRIPS		$0.00016P_b$	X		(V10)
APPLY DISPOSABLE BAG		$0.000006A_b$	X		(V11)
APPLY RUBBER BAG		$0.000015A_b$		X	(V12)
SEAL EDGES		$0.00054P_b$	X		(V13)
CLAMP EDGES		$0.00023P_b$		X	(V14)
CONNECT VACUUM LINES & APPLY VACUUM		0.0061	X	X	(V15)
SMOOTH DOWN		$0.000006A_b$	X	X	(V16)
CHECK SEALS		$0.000017P_b$	X	X	(V17)
DISCONNECT VACUUM LINES		0.0031	X	X	(V18)
CHECK AUTOCLAVE INTERIOR		0.0300			(A1)
LOAD LAYUP IN TRAY		$0.000145A^{0.6711}$			(A2)
ROLL TRAY IN		0.0250			(A3)
CONNECT THERMOCOUPLE LEADS		$0.0092N_f$			(A4)
CONNECT VACUUM LINES AND APPLY VACCUM PRESSURE		$0.0061N_f$			(A5)
CHECK BAG, SEAL & FITTINGS		$[0.000006A_b + 0.00027P_b + 0.0088N_f]$			(A6)
CLOSE AUTOCLAVE		0.0192			(A7)
SET RECORDERS		0.0560			(A8)
START CURE CYCLE					

DETAIL ELEMENT	SETUP	RUNTIME	APPLICATION DISP.	REUS.	
CYCLE CHECK		0.0800			(A9)
SHUT DOWN		0.00332			(A10)
REMOVE CHARTS		0.00332			(A11)
OPEN AUTOCLAVE DOOR		0.0192			(A12)
DISCONNECT THERMOCOUPLE LEADS		$0.0035N_f$			(A13)
DISCONNECT VACUUM LINES		$0.0031N_f$			(A14)
ROLL TRAY OUT OF AUTOCLAVE		0.0120			(A15)
REMOVE LAYUP FROM TRAY		$0.000145A^{0.6711}$			(A16)
RELEASE CLAMPS		$0.00007P_b$		X	(V19)
REMOVE DISPOSABLE BAG		$0.000008A_b$	X		(V20
REMOVE REUSABLE BAG		$0.000003A_b$		X	(V21)
REMOVE THERMOCOUPLES		$0.0095N_f$	X	X	(V22)
REMOVE VACUUM FITTINGS		$0.0029N_f$	X		(V23)
REMOVE VENT CLOTH		$0.000007A_b$	X	X	(V24)
REMOVE NON-POROUS SEPARATOR FILM		$0.000007A_b$	X	X	(V25)
REMOVE BLEEDER PLIES		$0.000007A_b$	X	X	(V26)
REMOVE POROUS SEPARATOR FILM		$0.000007A_b$	X	X	(V27)
ASIDE USED MATERIAL		$0.000005A_b$	X	X	(V28)
REMOVE LAYUP & ASIDE		$0.000006A_b$	X	X	(V29)
CLEAN TOOL		$0.000006A_b$	X	X	(V30)

WHERE:

A = Area of detail part to be consolidated, in square inches
A_a = Area of surface where adhesive is applied, in square inches
A_b = Bagging area, in square inches
A_r = Area of resin bleeder plies
= Area of composite material used divided by ply to bleeder ratio, in square inches
N_f = Number of vacuum fittings = 1, if $A_b < 432$ square inches
= 2, if $A_b \geq 432$ square inches
P_b = Perimeter of bag to be sealed or clamped, in inches

NOTES:

1. (V1) - (V3) are applicable if two or more component detail parts are to be joined together in one cure cycle
2. (V4) - (V5) and (V26) - (V27) are applicable if resin bleeding.

VACUUM BAG/OVEN CURE

DETAIL ELEMENT	SETUP	RUNTIME	
SETUP	0.05		
SEE VACUUM BAG/AUTOCLAVE CURE FOR ELEMENTS (V1) - (V18)			
CHECK OVEN INTERIOR		0.0300	(01)
LOAD LAYUP INTO OVEN		$0.000114A_b^{0.8586}$	(02)
CONNECT VACUUM LINES AND APPLY VACUUM PRESSURE		$0.0061N_f$	(03)
CONNECT THERMOCOUPLE LEADS		$0.0092N_f$	(04)
CHECK FOR LEAKS		$[0.000006A_b + .00044P_b + 0.0088N_v]$	(05)
CLOSE OVEN		0.0192	(06)
SET RECORDER		0.0140	(07)
START CYCLE			
CYCLE CHECK		0.0800	(08)
SHUT DOWN AFTER CURE		0.00083	(09)
REMOVE CHARTS		0.00083	(010)
OPEN OVEN		0.0192	(011)
DISCONNECT THERMOCOUPLE LEADER		$0.0035N_f$	(012)
DISCONNECT VACUUM LINES		$0.0031N_f$	(013)
REMOVE PART FROM OVEN		$0.000114A_b^{0.8586}$	(014)
SEE VACUUM BAG/AUTOCLAVE CURE FOR ELEMENTS (V19) - (V30)			

WHERE:

A_b = Bagging area, in square inches

N_f = Number of vacuum fittings

P_b = Sealing/clamping perimeter, in inches

THERMAL EXPANSION MOLDING

DETAIL ELEMENT	SETUP	RUNTIME	
SETUP	0.02		
CLEAN MOLD CAGE		$0.0008A_m$	(X1)
APPLY RELEASE AGENT		$0.0013A_m$	(X2)
ASSEMBLE LAYUPS INTO CAGE		$[0.0237 \quad (A^{0.6083})] + 0.0016$	(X3)
APPLY HEAT:			
a. OVEN:	0.05	SEE VACUUM BAG/OVEN CURE ELEMENTS (01) - (014)	
b. HEATING ELEMENT:	0.43	$0.00264 \quad (A^{0.3207})$	(X4)
REMOVE PART FROM TOOL		$[0.000145 \quad (A^{0.6711})] + 0.000253$	(X5)
ASIDE PARTS		$0.000043 \quad A^{0.5985})$	

WHERE:

A_m = External surface area of mold cage, in square inches

A = Area of component detail part to be consolidated, in square inches

2.1.4 FINISHING OPERATIONS

Finishing includes all operations performed on a cured composite part to bring it to final dimensional specifications. Finishing operations have been grouped into two parts: trimming operations and hole preparation.

Trimming is the final sizing of a cured composite part. Several techniques are used in trimming depending on part size, thickness, amount of cured material to be trimmed, equipment available, tool geometry, etc. The techniques analyzed in this program include: routing, sawing, and sanding. The basic difference between each of these techniques lies in the tool used.

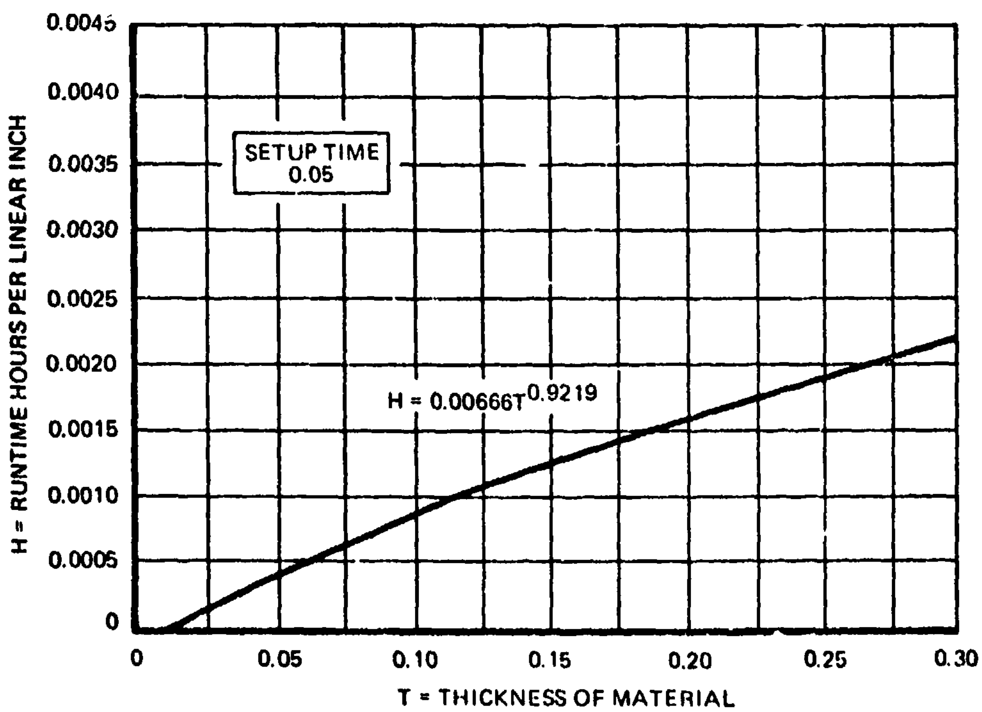
Hole operations are performed as required by specifications. In addition to basic drilling and hole punching, other additional operations are sometimes required. These include: reaming, counterboring, countersinking, and hole sawing.

Standards equations for each of the finishing operations are discussed in this section. Total operating time requires the addition of handling time to account for part handling, and if fixtures, templates, inserts, or clamps are used. The handling time equations, as well as each of the equations for net trim and hole operations are presented in the Summary of Finishing Standards.

2.1.4.1 NET TRIM OPERATIONS

ROUTING: Routing is a process of removing material using high speed cutters guided by templates or block providing a cutting pattern. Routing is generally performed for edge trimming or cutouts, and may be accomplished by hand or by machine.

Hand routing uses a portable tool (hand router) provided with guide rollers, bars, or straps which bear against a guide on a tool by hand pressure. The standards for hand routing are illustrated in Figure 24 and relate the routing rate with the thickness of the cured composite part being routed. Total runtime hours is obtained by multiplying the results of this equation by the length of cut. Setup time is 0.05 hour.



(F1)

FIGURE 24. STANDARDS EQUATION FOR HAND ROUTING

Machine routing uses a floor mounted machine with a high speed cutter mounted in a spindle above the work table. The routing pattern is determined by a pin and template. The cutter and pin remain stationary and concentric, while only the part (attached to the template with pattern) is moved. The standard runtime to machine rout is defined by the equation:

$$H = 0.0015L, \qquad \text{(F2)}$$

WHERE:

H = Standard runtime hours per part

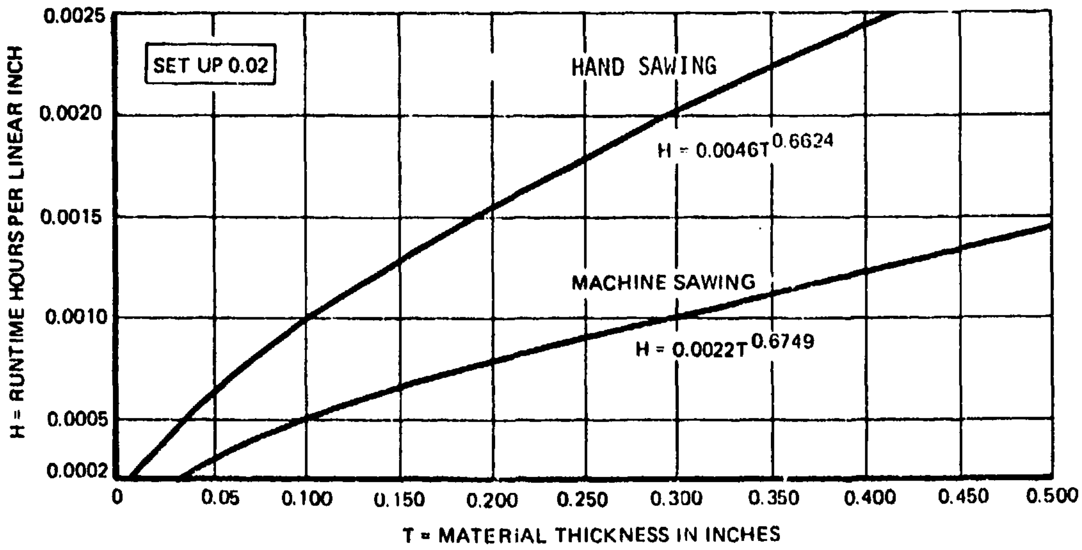
L = Router course length, in inches

Setup Time = 0.05 Hour

SAWING: When a substantial amount of composite material is to be removed, sawing operations are usually performed. Sawing may be done by hand or by machine guided by lines, guide bars, templates or fixtures. The sawing operations analyzed in this study are applicable only to straight cuts.

Hand sawing is performed with a pneumatic tool equipped with a 2" - 3" diamond abrasive wheel. The standard runtime equation for this operation is presented in Figure 25 (upper curve) and relates the sawing runtime rate to the thickness of the material to be sawed. Total sawing time is obtained by multiplying the results of this equation by the length of the cut. Setup time is 0.02 hour.

Machine sawing uses a radial saw (radial arm) equipped with a carborundum abrasive wheel. The standard runtime equation for this operation is likewise presented in Figure 25 (lower curve). Setup time is 0.05 hour.



(F3)

(F4)

FIGURE 25. STANDARDS EQUATIONS FOR SAWING

SANDING: Sanding is a final sizing process used to smooth rough edges, resin flashings and frayed areas. There were three methods of sanding studied in this program: hand sanding, portable tool sanding and machine sanding.

HAND SANDING is performed solely for deburring or cleaning edges where a small amount of material is to be removed. Wet or dry sandpaper is used for this operation. The standard runtime equation for hand sanding is:

$$H = 0.0005L \qquad \text{(F5)}$$

WHERE:

H = Standard runtime hours per part

L = Sanding length, in inches

Setup Time = 0.02 Hour

PORTABLE TOOL SANDING is accomplished with a pneumatic disc sander guided by a scribe line or template. This operation is used for large or odd shaped parts that cannot be accomodated on a machine sander. Portable tool sanding runtime is a function of both the thickness of the material and the length of the edge to be sanded as shown below:

$$H = (0.0012T)L \qquad \text{(F6)}$$

WHERE:

H = Standard runtime hour per part

T = Thickness of material, in inches

L = Length to be sanded, in inches

Setup Time = 0.02 Hour

MACHINE SANDING is required when large amounts of material are to be removed, but not enought to permit the excess to be sawed. The machine analyzed in this program is a bridge port mill with a drum coated abrasive band fitted on a precision mandrel.

The maximum amount of material removed per pass is 0.0703 square inch with the depth of feed limited to 0.25 inch per pass. The standard runtime equation for this operation is:

$$H = (0.000046L)\ P \qquad \text{(F7)}$$

WHERE:

H = Standard runtime hours per part

L = Length of each pass, in inches

P = Number of passes

$$= \frac{\text{Depth of Cut} \times \text{Thickness}}{0.0703} \quad \text{(rounded to the next higher number)}$$

Setup Time = 0.25 Hour

2.1.4.2 HOLE OPERATIONS

DRILLING: This is the process by which holes are produced in a part using a drill motor which imparts rotary motion to the carbide drill bit that is forced against the part. This operation is used extensively in the airframe industry to provide a means of assembling component parts with fasteners. Equations have been developed for drilling operations and the handling time associated with the operation. The equation for drilling represents decimal hours per hole and is a function of diameter and depth of the hole. The machine runtime encompasses the drill time to approach, penetrate to required depth, retraction and aside part. If more than one hole is to be drilled, a

repositioning time will be required for each new hole. This time is incorporated in the drilling standard equation. The drilling standards apply to controlled feed and speed machines such as the Quackenbusch and Tornetie System installed on a drill press. A nomograph representing the standards equation is presented in Figure 26 below. The nomograph has been prepared to provide a convenient means of manual estimating. Total runtime is obtained by multiplying the results of this equation by the quantity of holes drilled.

SETUP TIME
0.05 HOUR

$$H = 0.01693 D^{0.3370} Z^{0.4562} \qquad \text{(F8)}$$

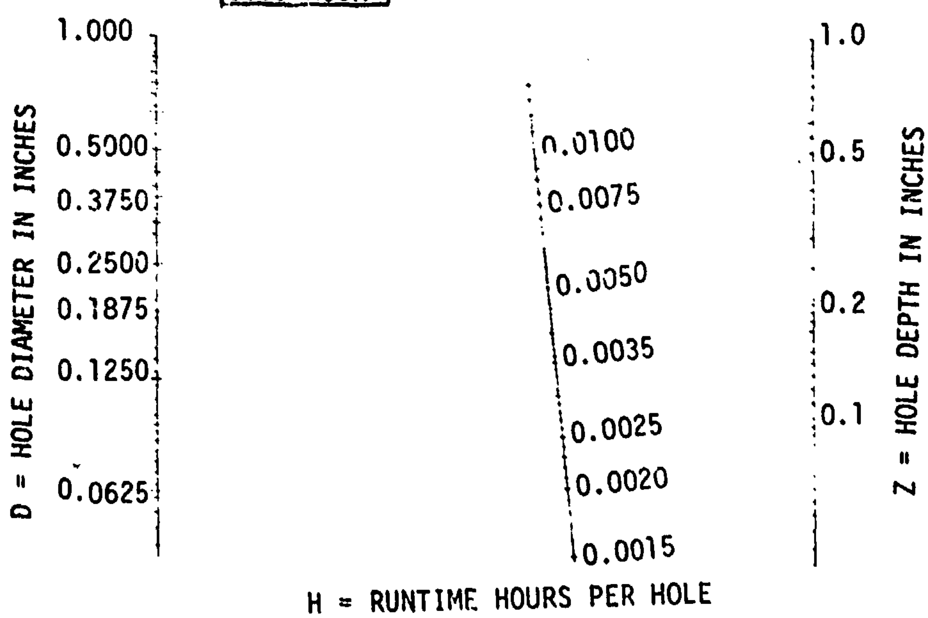


FIGURE 26. NOMOGRAPH OF STANDARDS EQUATION FOR HOLE DRILLING

COUNTERBORING: Counterboring is the process of enlarging one end of a drilled hole. This enlarged hole is concentric with the original hole and is flat on the bottom. This operation is used primarily if fastener heads and/or nuts are required to be set below the surface. The tool used in this operation is similar to an end mill and is provided with a pilot pin which fits into the drilled hole to guide the cutting edges. A carbide tool was used in controlled speed and feed machines to develop the standards for counterboring on cured parts in this program. The resultant equation represents the runtime per hole as a function of the diameter and depth of the counterbored hole. The standards equation, represented in the nomograph in Figure 27, covers the time to obtain and position the part, counterboring, and aside part. Total runtime is obtained by multiplying the results of this equation by the quantity of holes that are counterbored.

$$H = 0.00514D^{0.5966}Z^{0.2756} \qquad (F9)$$

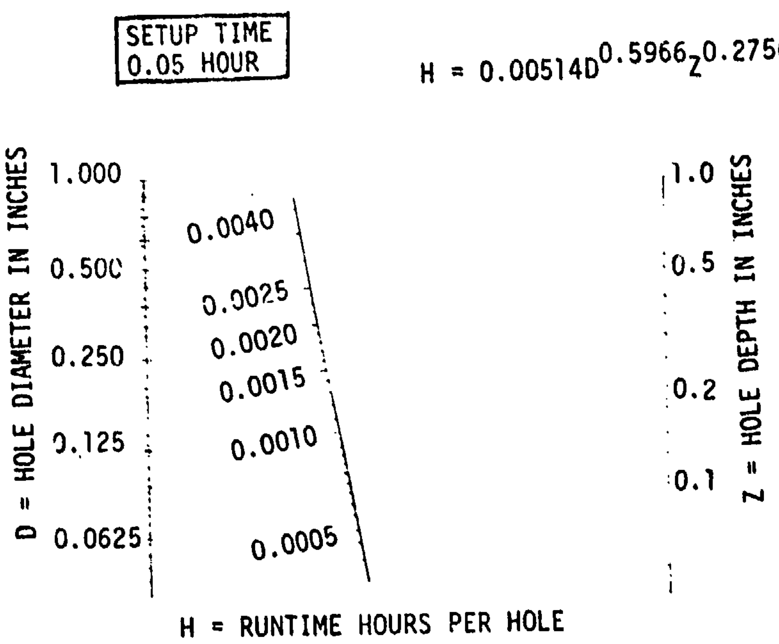


FIGURE 27. NOMOGRAPH OF STANDARDS EQUATION FOR COUNTERBORING

REAMING: Reaming is the operation of enlarging a machined (drilled, punched, etc.) hole to proper size with a smooth finish. A reamer is an extremely accurate tool and is not designed to remove a substantial amount of cured composite material. A carbide tool held in a fixture mounted in controlled speed and feed machines was used to develop the standards for reaming. The standard equation that was developed represents the machine runtime per hole as a function of the diameter and depth of hole to be reamed, and is shown in the nomograph in Figure 28 . Total runtime is obtained by multiplying the results of this equation by the quantity of holes reamed. Setup time is 0.05 hour.

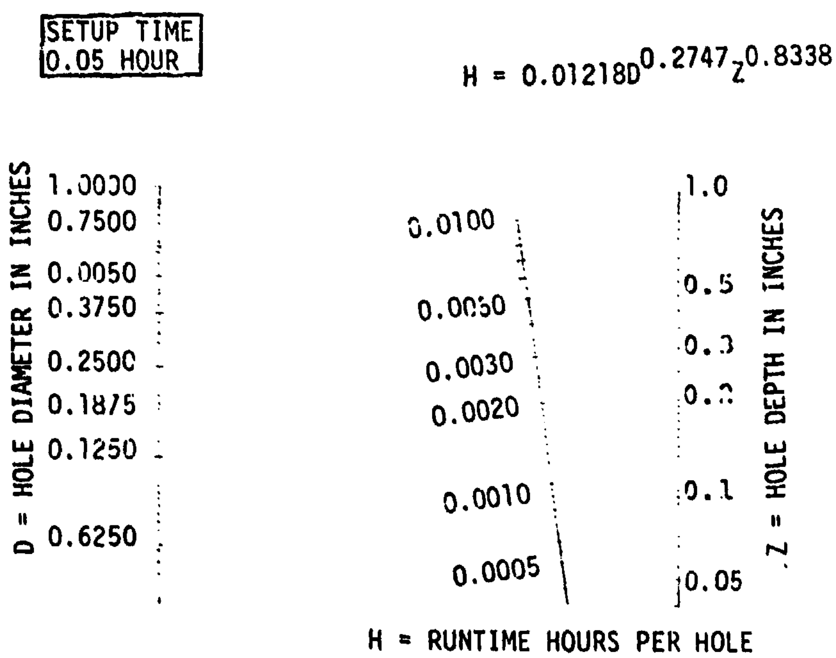
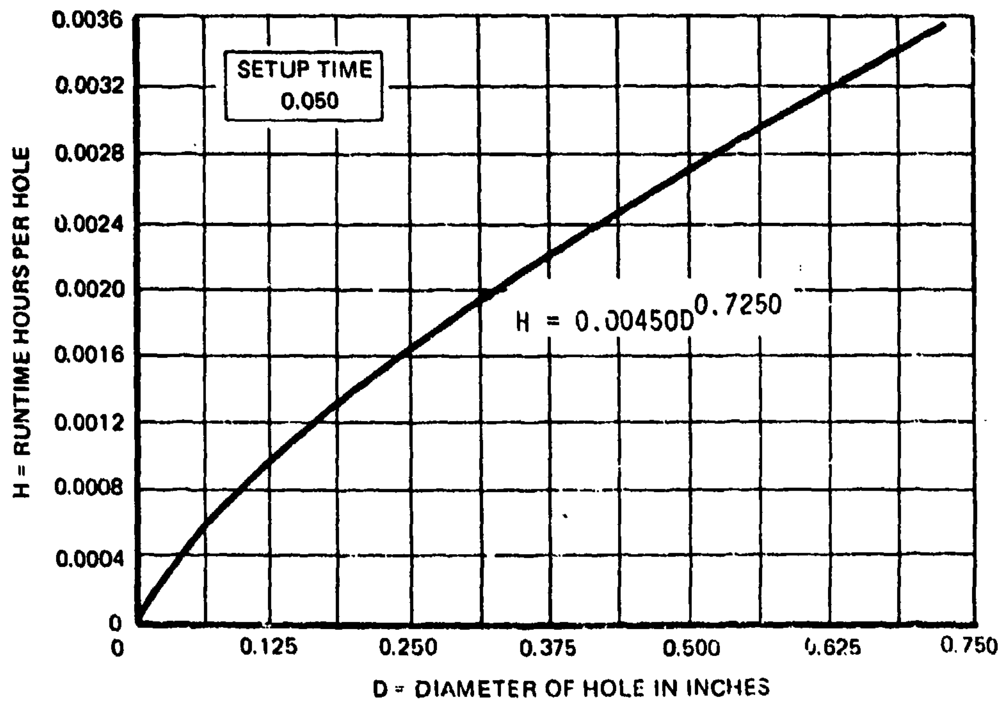


FIGURE 28. NOMOGRAPH OF STANDARDS EQUATION FOR REAMING

COUNTERSINKING: Countersinking is required if the top of a drilled hole is beveled to accommodate the conical seat of a flat head screw in order to have the head of the screw flush with the surface. A carbide tool held in a spindle mounted in controlled speed and feed machines was used to develop the standards for countersinking in this program. This operation is generally performed as a part of the drilling operation cycle. The standards equation that was developed represents the machine runtime per hole as a function of the drilled hole size, and is graphically illustrated in Figure 29. Total runtime is obtained by multiplying the results of this equation by the quantity of holes countersinked. Setup time is 0.05 hour.



$$H = 0.00450D^{0.7250} \quad \text{(F11)}$$

FIGURE 29. STANDARDS EQUATION FOR COUNTERSINKING

HOLE PUNCHING: Hole punching is an alternative to drilling and is especially adaptable to thin parts. This operation can also be used to establish pilot holes for routers cutout operations. The standards for this operation reflect the time to place part on the machine bed, select the correct punch size (by rotating punch magazine) and punch holes. The standards equation for hole punching is as follows:

$$H = 0.0036(N) \qquad \text{(F12)}$$

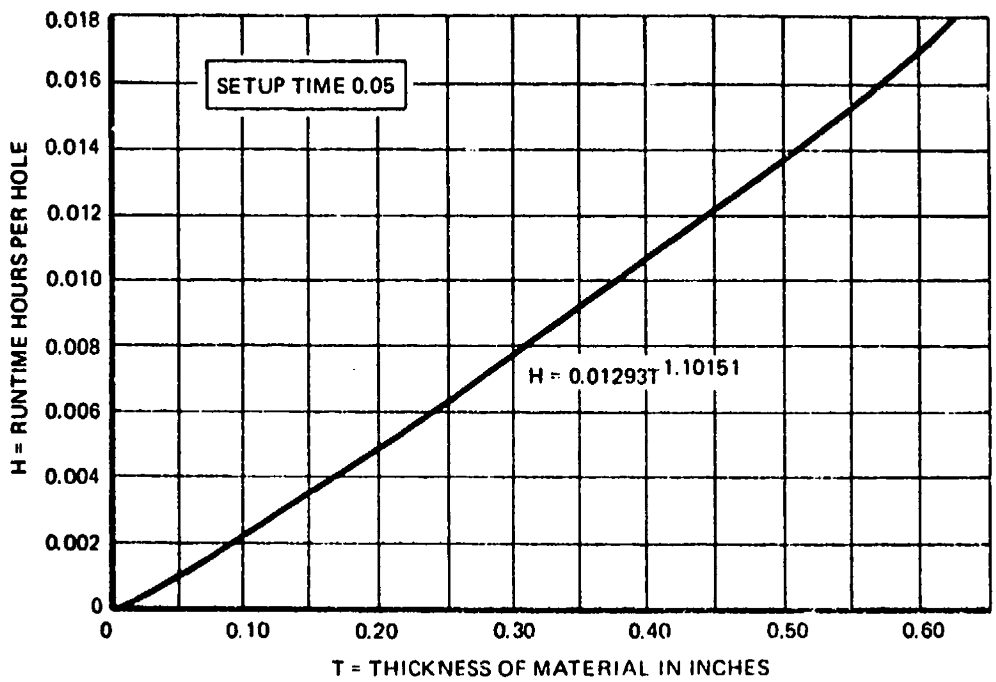
WHERE:

H = Runtime hours per part

N = Number of holes punched

Setup time is 0.05 hour

HOLE SAWING: When a hole is too large to be cut by a standard size drill, hole sawing operations are performed. The tool used in this operation is a circular metal band with saw teeth on the edge with either a drill or pilot pin concentric with the saw band in the center of the tool. The tool is held in a spindle or chuck in either a portable or stationary drill motor. The standards equation developed for hole sawing reflect the use of a saw with a pilot pin and includes the drilling of a pilot hole. The equation is graphically illustrated in Figure 30. Total runtime hours is obtained by multiplying the results of the equation by the quantity of holes sawed. Setup time is 0.05 hour.



(F13)

FIGURE 30. STANDARDS EQUATION FOR HOLE SAWING

2.1.4.3 SUMMARY OF FINISHING STANDARDS ESTIMATING RELATIONSHIPS

DETAIL ELEMENT	SETUP	RUNTIME	
NET TRIM OPERATIONS			
HAND ROUTING	0.05	$(0.00666T^{0.9219})L$	(F1)
MACHINE ROUTING	0.20	$0.0015L$	(F2)
HAND SAWING	0.02	$(0.0046T^{0.6624})L$	(F3)
MACHINE SAWING	0.05	$(0.0022T^{0.6749})L$	(F4)
HAND SANDING	0.02	$0.0005L$	(F5)
PORTABLE TOOL SANDING	0.02	$(0.0012T)L$	(F6)
MACHINE SANDING	0.25	$(0.00046L)P$	(F7)
HOLE OPERATIONS			
DRILLING	0.05	$(0.01693D^{0.3370}Z^{0.4562} + 0.0006)Q$	(F8)
COUNTERBORING	0.05	$(0.00514D^{0.5966}Z^{0.2756} + 0.0006)Q$	(F9)
REAMING	0.05	$(0.01218D^{0.2747}Z^{0.8338} + 0.0006)Q$	(F10)
COUNTERSINKING	0.05	$(0.00450D^{0.7250} + 0.0006)Q$	(F11)
HOLE PUNCHING	0.05	$(0.0036)Q$	(F12)
HOLE SAWING	0.05	$(0.01293Z^{1.10151} + 0.0006)Q$	(F13)
HANDLING TIME			
PART HANDLING		$0.000145A^{0.6711}$	(F14)
FIXTURE - INTERNAL		$0.00414A^{0.3264}$	(F15)
- EXTERNAL		$0.00777A^{0.2894}$	(F16)
TEMPLATE		$0.000107A^{0.77006}$	(F17)
CLAMPS		$0.000322C$	(F18)
INSERTS		$0.0007Q$	(F19)

WHERE:

T = Average material thickness, in inches
L = Trim length, in inches
P = Number of passes
D = Hole diameter, in inches
Z = Hole depth, in inches
Q = Quantity of holes per part
A = Part area, in square inches
C = Part perimeter, in inches

2.2 FACTORY LABOR VARIANCE

Estimates of direct factory labor hours are developed through the application of appropriate variances to the standards at specified production units. The calculation of variances is part of the computerized system and is accomplished using the variance equations developed in this program for layup, honeycomb core preparation, part consolidation, and finishing. The discussion below illustrates the procedures for calculating unit, cumulative, and cumulative average variances for each of the four fabrication processes.

LAYUP VARIANCES: The unit variance for layup at a specified unit N is calculated using the following equation:

$$V_{UL} = 34.03\ N^{-.6037} \quad \text{for} \quad N \leq 5$$

$$V_{UL} = 23.24\ N^{-.3840} \quad \text{for} \quad N \geq 6$$

The application of these unit variances to layup standards gives the unit layup hours for any unit N.

Cumulative layup hours for N units is estimated by applying to standards the corresponding cumulative variances calculated through the following equations:

$$V_{CL} = [34.03 \sum_{1}^{N} (i^{-.6037})] \quad \text{for } N \leq 5$$

$$V_{CL} = [34.03 \sum_{i=1}^{5} (i^{-.6037})] + [23.24 \sum_{6}^{N} (i^{-.3840})] \quad \text{for } N \geq 6$$

The cumulative average variances for N units is calculated as follows:

$$V_{CAL} = \frac{V_{CL}}{N}$$

SYMBOLS: V_{UL} = Unit layup variance

V_{CL} = Cumulative layup variance

V_{CAL} = Cumulative average layup variance

N = Unit number

Cumulative average variance for N units is calculated as follows:

$$V_{CAPC} = \frac{V_{CPC}}{N}$$

SYMBOLS:

V_{UPC} = Unit part consolidation variance

V_{CPC} = Cumulative part consolidation variance

V_{CAPC} = Cumulative average part consolidation variance

N = Unit number

FINISHING VARIANCES

Unit variance for finishing operations is calculated as follows:

$$V_{UF} = [35.19N^{-.6035}] \quad \text{for} \quad N \leqslant 5$$

$$V_{UF} = [23.84N^{-.3813}] \quad \text{for} \quad N \geqslant 6$$

Cumulative variance for N units is calculated as follows:

$$V_{CF} = [35.19 \sum_{1}^{N} (i^{-.6035})] \quad \text{for} \quad N \leqslant 5$$

$$V_{CF} = [35.19 \sum_{i=1}^{5} (i^{-.6035})] + [23.84 \sum_{6}^{N} (i^{-.3813})] \quad \text{for} \quad N \geqslant 6$$

Cumulative average variance for N units is calculated as follows:

$$V_{CAF} = \frac{V_{CF}}{N}$$

SYMBOLS:

V_{UF} = Unit finishing variance

V_{CF} = Cumulative finishing variance

V_{CAF} = Cumulative average finishing variance

N = Unit number

HONEYCOMB CORE VARIANCES: The unit variance for honeycomb core operations at unit N is calculated as follows:

$$V_{UHC} = 1.3970 + \frac{15.4359}{N}$$

Cumulative variance for N units is calculated using the equation:

$$V_{CHC} = 1.397N + 15.4359 \sum_{1}^{N} \frac{1}{i}$$

Cumulative average variance is calculated as follows:

$$V_{CAHC} = \frac{V_{CHC}}{N}$$

SYMBOLS:

V_{UHC} = Unit honeycomb core variance

V_{CHC} = Cumulative honeycomb core variance

V_{CAHC} = Cumulative average honeycomb core variance

N = Unit number

PART CONSOLIDATION VARIANCES:

The unit variance for the part consolidation operations is calculated as follows at unit N.

$$V_{UPC} = [36.48N^{-.6044}] \text{ for } N \leqslant 5$$

$$V_{UPC} = [25.06N^{-.3860}] \text{ for } N \geqslant 6$$

Cumulative variance for N units is calculated as follows:

$$V_{CPC} = [36.48 \sum_{1}^{N} (i^{-.6044})] \text{ for } N \leqslant 5$$

$$V_{CPC} = [36.48 \sum_{i=1}^{5} (i^{-.6044})] + [25.06 \sum_{6}^{N} (i^{-.3860})] \text{ for } N \geqslant 6$$

The variance factors and improvement curve slopes defined by the above equations represent allowances that are applied to pure labor to account for activities other than the actual operations required to manufacture a part. These allowances cover coffee breaks, waiting time for tools and materials, rework, supervision, attention to personal needs, time lost due to fatigue, and absenteeism, clean up time, etc.

The development of the variance and improvement curve equations were based on fiberglass and core fabrication data. Fiberglass experience was selected as a base for developing variances for composite related operations, i.e., layup, part consolidation, and finishing, because of its close similarity to composites particularly in methods of fabrication. Variances for each process, i.e., actual hours divided by standards were plotted on logarithmic charts as shown in Figures 31 - 34.

Analysis of these plots show the distinctive behavior of variance points in relation to production units, i.e., the initial units have greater fluctuations about a least squares line and show a much steeper slope compared to the latter production units. To more closely simulate these actual experiences and be sensitive to these observed characteristics, the "dog-leg" approach was fitted through the initial 10 plot points (representing units 1 through 10) and then through subsequent points. The two best fit curves were then made to intersect to determine the break point in the "dog-leg" curve. An alternative approach that was investigated was the hyperbolic function of the forms $Y = A + \frac{B}{X}$ and $\frac{X}{A + BX}$. These curves have a shape in the logarithmic grid that is similar to a logarithmic "dog-leg", i.e., the slope of these curves starts out steep and gradually flattens out as the number of units increase. Table 1 shows the different curves equation fitted through these points and their corresponding coefficients of correlation. The "dog-leg" break points are also indicated. The selected regressions for each fabrication process are drawn in Figures 31 - 34.

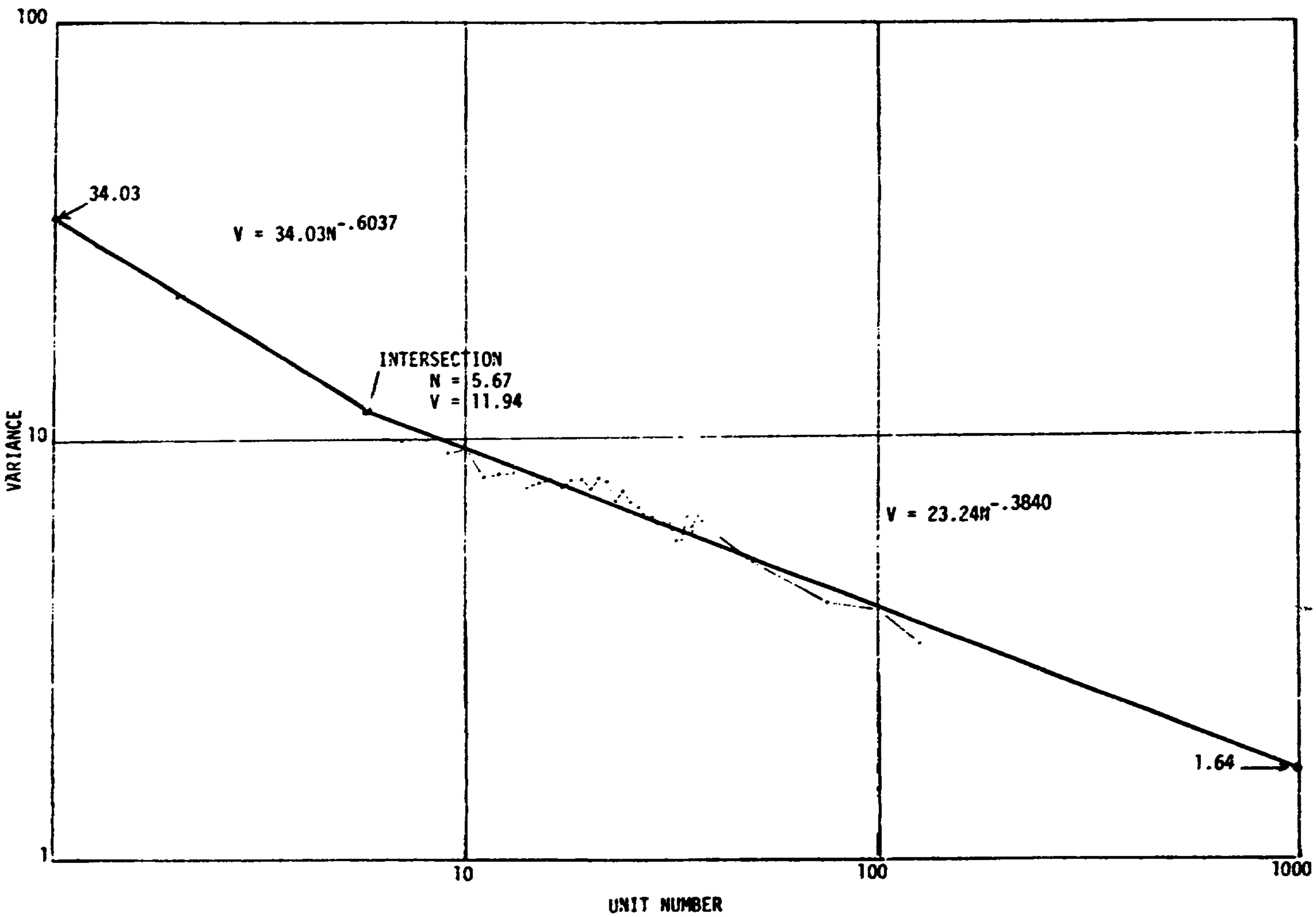


FIGURE 31. LAYUP VARIANCE CURVE

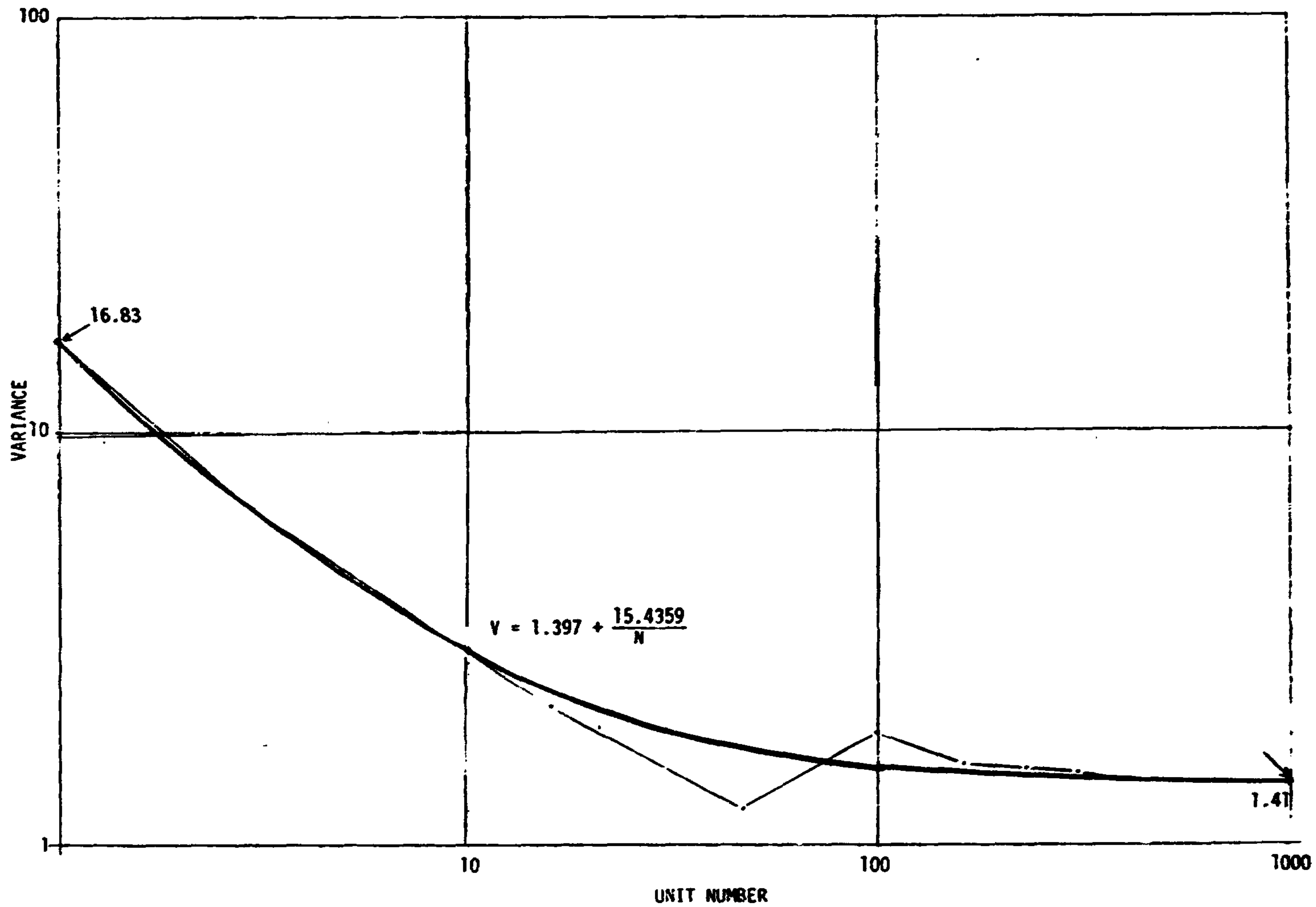


FIGURE 32. CORE PREPARATION VARIANCE CURVE

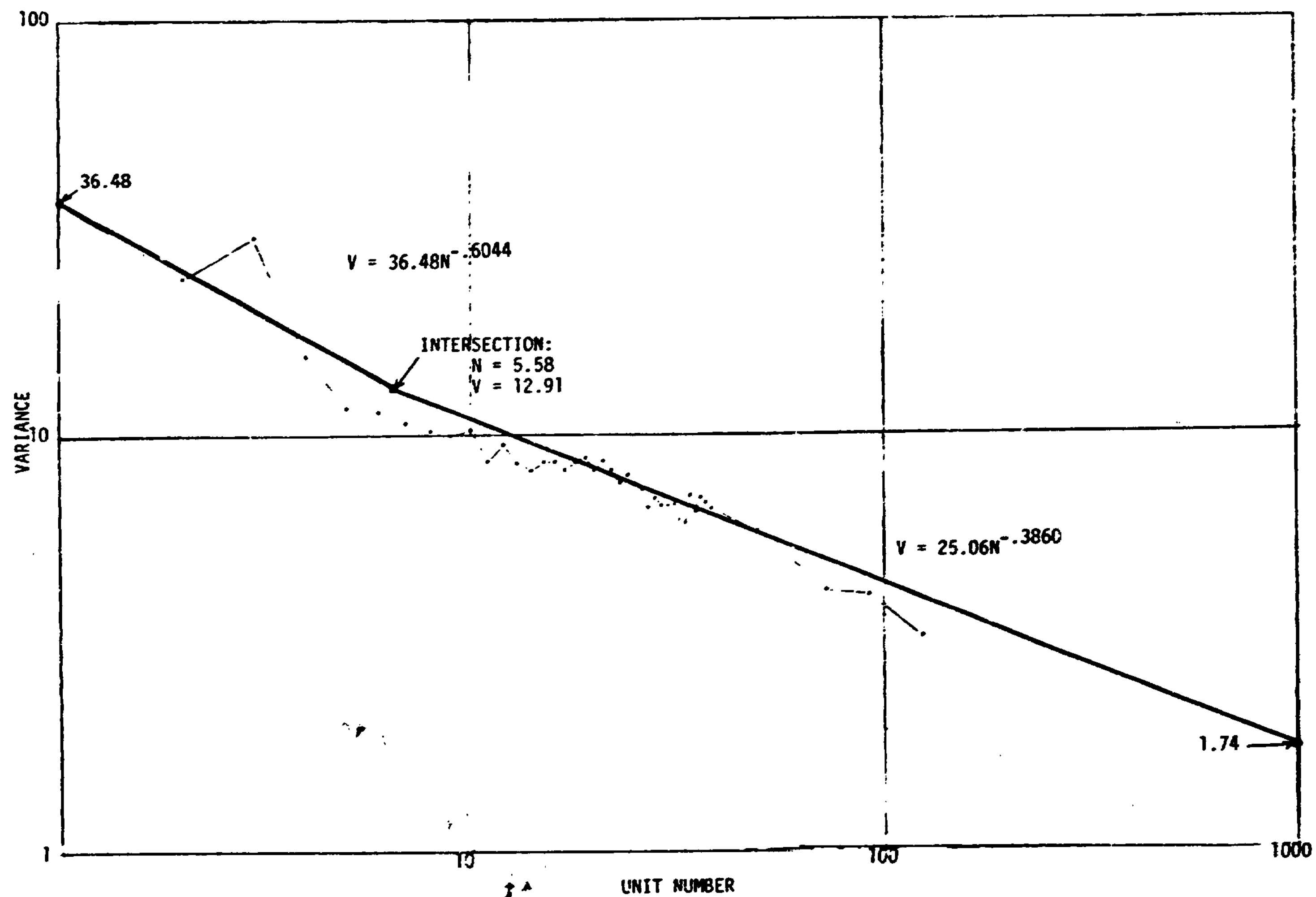


FIGURE 33. PART CONSOLIDATION VARIANCE CURVE

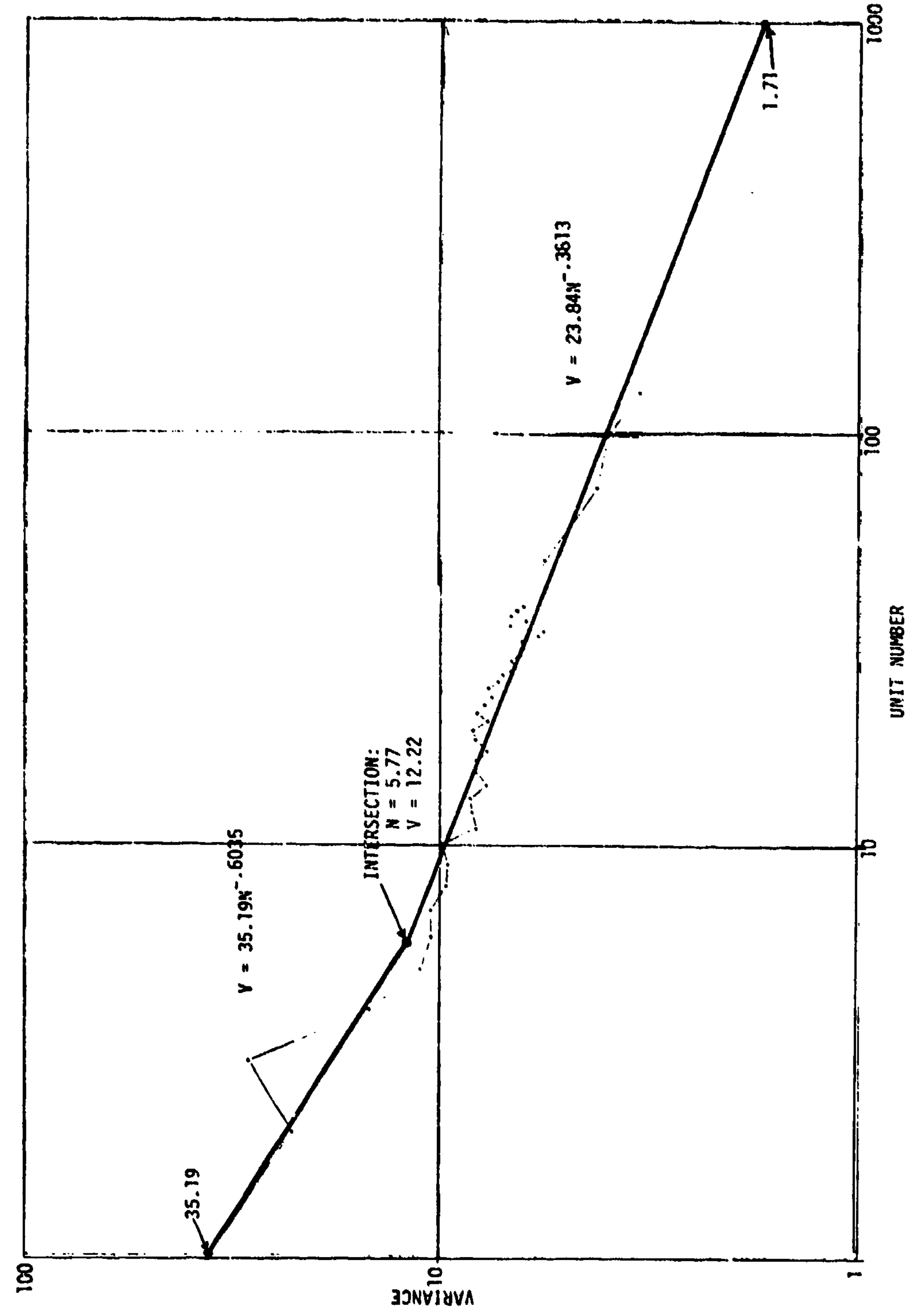


FIGURE 34. FINISHING OPERATIONS VARIANCE CURVE

TABLE 1.

VARIANCE CURVES

	"DOG - LEG" 1st Curve	2nd Curve	INT. PT. (N =)	HYBERBOLIC $A + B/N$	$\frac{N}{A + BN}$
LAYUP	$34.03N^{-.6037}$	$23.24N^{-.3840}$	5.67	$5.58 + \frac{32.59}{N}$	$\frac{N}{-.191 + .159N}$
.Corr.Coeff	83.8%	88.4%		85.7%	59.7%
PART CONS.	$36.48N^{-.6044}$	$25.06N^{-.386}$	5.58	$5.98 + \frac{34.82}{N}$	$\frac{N}{-.178 + .148N}$
Corr.Coeff.	84%	88.8%		85.8%	59.7%
FINISHING	$35.19N^{-.6035}$	$2[illegible].84N^{-.3813}$	5.77	$3.05 + \frac{16.0}{N}$	$\frac{N}{-.348 + .290N}$
Corr.Coeff	82.4%	85.6%		84.9%	58.9%
CORE	$12.69N^{-.6144}$	$4.35N^{-.1876}$	12.29	$1.397 + \frac{15.4359}{N}$	$\frac{N}{-1.55 + .658N}$
Corr.Coeff.	99%	95.0%		99%	87.8%

2.3 SUPPORT FUNCTIONS ESTIMATING

The Support Functions Estimating routine is composed of cost estimating relationships (CER's) that provide the user with the capability of estimating the recurring support functions associated with the fabrication of an advanced composite part. These estimating relationships cover labor functions as well as support material cost. The support labor functions include Engineering, Tooling, Manufacturing Engineering, Quality Control, and Graphic Services. The material category refers to the material expended in support of recurring labor functions. The CER's for each of these support functions were developed from fiberglass production data. However, the user has the option of utilizing his experience by applying his own factors or equations into the system. Instructions for making this override are provided in Volume II - User's Manual.

2.3.1 DEVELOPMENT OF COST ESTIMATING RELATIONSHIPS

Cost Estimating Relationships (CER's) are quantitative expressions that relate recurring support labor and material costs to part parameters and other cost elements. The development of CER's involved the evaluation and analysis of pertinent data made available through the cost data research activities undertaken in this program. Northrop was the primary source of data, particularly its T-38/F-5 production program, R & D and prototype composite programs, and fiberglass production programs.

The T-38/F-5 production program provided a very comprehensive set of data from which to develop support function CER's. Relating this metallic experience to composites, however, presented a problem that eventually led to the search for other data.

Pertinent data with respect to support functions was obtained from R & D and prototype composite programs. However, the limited scope and nature of this data made it unsuitable for projecting CER's past the 4th and 5th production unit.

Northrop's fiberglass experience offered extensive cost data on support functions. Labor costs, particularly, had been tracked accurately and in sufficient detail to provide this program with a sound base for developing CER's. The support function CER's developed from this data base are applicable to composites because of close similarities in material, manufacturing processes, and applications.

Northrop's fiberglass production experience provided actual hours (by unit number) for Factory Labor, Quality Control, Engineering, Tooling, Manufacturing Engineering and Graphics Services. (This data is compiled in Volume III of this report). Scatter diagrams of those data were first plotted to examine the interrelationships of these cost elements. Least squares lines were fitted through the plot points of significant relationships. The equations that define these lines are expressions of the proportional relationships between the labor hours of each support function and the factory labor hours, by unit number. Two separate sets of equations were derived; their application depends upon the estimator's use of log-linear unit or log-linear cumulative average improvement curves. These CER's are presented in the following sections.

2.3.2 QUALITY CONTROL

Recurring Quality Control is the effort required to ensure the conformance to drawings and specifications of raw material, purchased parts, and company fabricated parts during the manufacturing process.

The CER's for Recurring Quality Control are as follows:

Log- Linear Unit Improvement Curve

Unit Quality Control Labor Hours

$$QCLH_{N\text{-}Unit} = (0.3542N^{-0.2285})\ (FLH_{N\text{-}Unit})$$

Cumulative Quality Control Control Labor Hours

$$QCLH_{N\text{-}Cum} = (0.3542\sum_{i=1}^{N} i^{-0.2285})\ (FLH_{N\text{-}Cum})$$

Cumulative Average Quality Control Labor Hours

$$QCLH_{N\text{-}Cum\ Ave} = (QCLH_{N\text{-}Cum})\ /N$$

Log-Linear Cumulative Average Improvement Curve

Cumulative Average Quality Control Labor Hours

$$QCLH_{N\text{-}Cum\ Ave} = (0.4243N^{-0.1737})\ (FLH_{N\text{-}Cum\ Ave})$$

Cumulative Quality Control Labor Hours

$$QCLH_{N\text{-}Cum} = (0.4243N^{-0.1737})\ (FLH_{N\text{-}Cum})$$

Unit Quality Control Hours

$$QCLH_{N\text{-}Unit} = (QCLH_{N\text{-}Cum}) - (QCLH_{(N-1)\text{-}Cum})$$

2.3.3 TOOLING

Recurring Tooling Labor consists of the effort required in the repair and maintenance of tools, periodic tooling cycle checks to ensure continuing dimensional integrity, design and fabrication of new tools for improving manufacturing operations, and incorporation of any required company-generated design changes.

The CER's for Recurring Tooling are as follows:

Log-Linear Unit Improvement Curve

Unit Tooling Labor Hours

$$TLH_{N\text{-}Unit} = (0.6313N^{-0.4196})\ (FLH_{N\text{-}Unit})$$

Cumulative Tooling Labor Hours

$$TLH_{N\text{-}Cum} = (0.6313\sum_{i=1}^{N} i^{-0.4196})\ (FLH_{N\text{-}Cum})$$

Cumulative Average Tooling Labor Hours

$$TLH_{N\text{-}Cum\ Ave} = (TLH_{N\text{-}Cum})\ /N$$

Log-Linear Cumulative Average Improvement Curve

Cumulative Average Tooling Labor Hours

$$TLH_{N\text{-}Cum\ Ave} = (0.7030N^{-0.2594})\ (FLH_{N\text{-}Cum\ Ave})$$

Cumulative Tooling Labor Hours

$$TLH_{N\text{-}Cum} = (0.7030N^{-0.2594})\ (FLH_{N\text{-}Cum})$$

Unit Tooling Labor Hours

$$TLH_{N\text{-}Unit} = (TLH_{N\text{-}Cum}) - (TLH_{(N-1)\text{-}Cum})$$

2.3.4 MANUFACTURING ENGINEERING

Recurring Manufacturing Engineering consists of the effort to improve the manufacturing plan to ensure continuing methods improvement, assisting in the solution of problems related to the manufacturing operations involved in the production of the part and the processing of company generated changes.

The CER's for Recurring Manufacturing Engineering are as follows:

Log-Linear Unit Improvement Curve

Unit Manufacturing Engineering Labor Hours

$$MELH_{N\text{-}Unit} = (1.0062N^{-0.4256})\ (FLH_{N\text{-}Unit})$$

Cumulative Manufacturing Engineering Labor Hours

$$MELH_{N\text{-}Cum} = (1.0062\sum_{i-1}^{N} i^{-0.4256})\ (FLH_{N\text{-}Cum})$$

Cumulative Average Manufacturing Engineering Labor Hours

$$MELH_{N\text{-}Cum\ Ave} = (MELH_{N\text{-}Cum})\ /N$$

Log-Linear Cumulative Average Improvement Curve

Cumulative Average Manufacturing Engineering Labor Hours

$$MELH_{N\text{-}Cum\ Ave} = (0.7227N^{-0.1826})\ (FLH_{N\text{-}Cum\ Ave})$$

Cumulative Manufacturing Engineering Labor Hours

$$MELH_{N\text{-}Cum} = (0.7227N^{-0.1826})\ (FLH_{N\text{-}Cum})$$

Unit Manufacturing Engineering Labor Hours

$$MELH_{N\text{-}Unit} = (MELH_{N\text{-}Cum}) - (MELH_{(N-1)\text{-}Cum})$$

2.3.5 ENGINEERING

Recurring Engineering is the effort expended subsequent to the initial release of the drawings, exclusive of the support for test program, continuing through the duration of the production phase of the program. This effort consists of liaison and analysis in support of manufacturing and material procurement.

The CER's for Recurring Engineering are as follows:

Log-Linear Unit Improvement Curve

Unit Engineering Labor Hours

$$ELH_{N\text{-}Unit} = (0.3524N^{-0.3713})\ (FLH_{N\text{-}Unit})$$

Cumulative Engineering Labor Hours

$$ELH_{N\text{-}Cum} = (0.3524\sum_{i=1}^{N} i^{-0.3713})\ (FLH_{N\text{-}Cum})$$

Cumulative Average Engineering Labor Hours

$$ELH_{N\text{-}Cum\ Ave} = (ELH_{N\text{-}Cum})\ /N$$

Log-Linear Cumulative Average Improvement Curve

Cumulative Average Engineering Labor Hours

$$ELH_{N\text{-}Cum\ Ave} = (0.3540N^{-0.2223})(FLH_{N\text{-}Cum\ Ave})$$

Cumulative Engineering Labor Hours

$$ELH_{N\text{-}Cum} = (0.3540N^{-0.2223})\ (FLH_{N\text{-}Cum})$$

Unit Engineering Labor Hours

$$ELH_{N\text{-}Unit} = (ELH_{N\text{-}Cum}) - (ELH_{(N-1)\text{-}Cum})$$

2.3.6 GRAPHIC SERVICES

Recurring Graphic Services supports Engineering and Manufacturing with activities such as process and control of all engineering design drawings and data, preparation of art, text, and layouts for product-oriented publications, and reproduction, printing, photographic, and microfilm services.

The CER's for Recurring Graphic Services are as follows:

Log-Linear Unit Improvement Curve

Unit Graphic Services Labor Hours

$$GSLH_{N\text{-}Unit} = (0.0432N^{-0.1840})\ (FLH_{N\text{-}Unit})$$

Cumulative Graphic Services Labor Hours

$$GSLH_{N\text{-}Cum} = (0.0432\sum_{i=1}^{N} i^{-0.1840})\ (FLH_{N\text{-}Cum})$$

Cumulative Average Graphic Services Labor Hours

$$GSLH_{N\text{-}Cum\ Ave} = (GSLH_{N\text{-}Cum})\ /N$$

Log-Linear Cumulative Average Improvement Curve

Cumulative Average Graphic Services Labor Hours

$$GSLH_{N\text{-}Cum\ Ave} = (0.0824N^{-0.2298})\ (FLH_{N\text{-}Cum\ Ave})$$

Cumulative Graphic Services Labor Hours

$$GSLH_{N\text{-}Cum} = (0.0824N^{-0.2298})\ (FLH_{N\text{-}Cum})$$

Unit Graphic Services Labor Hours

$$GSLH_{N\text{-}Unit} = (GSLH_{N\text{-}Cum}) - (GSLH_{(N-1)\text{-}Cum})$$

2.3.7 SUPPORT MATERIAL

Support Material consists of raw material, purchased parts, equipment standard parts, and process material required to support the fabrication of composite parts. This category covers tooling, engineering and allocated material, and includes such items as vacuum film, Osnaburg cloth, thermocouple wire, teflon, potting compounds, and adhesive agents.

The CER for Recurring Support Material is as follows:

SM$ = 0.30 (DM$)

WHERE:

SM$ = Support Material Dollars

DM$ = Direct Material Dollars

2.3.8 MANUFACTURING ALLOWANCE

Manufacturing Allowance accounts for the cost of rework and scrap material experienced in the production environment.

The CER for Manufacturing Allowance is as follows:

MA$ = (0.02FL$) + (SCRAP$)

WHERE:

MA$ = Manufacturing Allowance

FL$ = Factory Labor Dollars

SCRAP$ = Scrap Material Dollars

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